

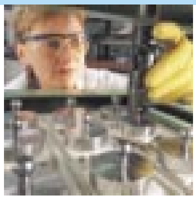


Dry Mortars

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Mortars based on mineral binders like lime, cement, or gypsum have been used for more than 8000 years in the construction of buildings. These mortars have mainly been used for laying stones and bricks (masonry mortars)and for coating walls (rendering mortars). Until the 1950s cement-based mineral mortars were exclusively produced and applied by so-called job-site mixing technology. Job-site mixing means transportation of the individual raw materials to the job-site and their mixing on site in the appropriate ratio. Thus cement, the most common mineral binder, is mixed with fillers (sand) before water is added to create the wet mortar for application.

Similar to the way in which job-site-mixed concrete was substituted by the economically and ecologically more favorable ready-mix concrete, job-site mixing techology for masonry and rendering mortars was replaced by factory-mixed dry mortars, also called dry-mix mortars. Dry-mix mortars or dry mortars are produced in specially designed dry-mix mortar plants in which mineral binder(s) and aggregates (sand) are mixed together in the appropriate way. This factory-based process also allows different additives and admixes to be added to these dry mortars to improve significantly their technical performance. Based on this technology individual dry mortars for specific applications can be produced according to formulations developed and pretested in the laboratory.

The factory-mixed dry mortars are delivered to the construction site in bags or in special silos and need only be mixed with water prior to use. Together with the appropriate equipment for efficient transport, mixing with water, and machine application of the wet mortar, this dry-mix mortar technology led to a drastic improvement in productivity in the application of highvolume products like masonry and rendering mortars.

The possibility of adding specific dry additives or admixes in a well defined ratio to the dry mix during the production also led to the development of highquality mineral mortars with well-defined and specific technical properties. These highly specialised mortars corresponding to the requirements of the modern building industry can not be produced with job-site mortar technology. Consequently, high-quality, additive - and admix-modified mineral mortars are today widely used in the building industry and have largely substituted other building materials such as ready-to-use paste compounds and liquid admixes used in combination with mineral mortars.

Development

Historical and Technical Development

For thousands of years the architecture and construction of buildings were closely associated with the use of mineral mortars. Lime plasters have been known for more than 8000 years, and gypsum mortars were used by the Babylonians about 6000 years ago. Hydraulic-setting mortars based on pozzolans (powdered volcanic ash) have probably been known for over 3000 years and were used in large amounts by the ancient Phoenicians, Greeks, and Romans.

In antiquity and the Middle Ages, additives and admixes such as soaps, resins, proteins, and ash were already mixed on the job site with mineral binders and aggregates to improve the technical performance of the resulting mortars.

Although a first patent on the manufacture and application of dry-mix mortars was published as early as 1893 in Europe, mortars were applied up to the 1950s exclusively as job-site-mixed mortars. For these mortars, the mineral binders (mostly cement) and aggregates (mostly quartz sand) are transported separately to the job site and are then mixed together by hand in the appropriate ratio. After mixing with water, the wet mortar is ready for application.

During the 1950s and 1960s in Western Europe and in the USA, but especially in Germany, there was a fast-growing demand in the construction industry for new building materials and technologies. The reasons for this included shortage of skilled workmen, the need for shorter construction times together with cost reduction, increasing labor costs, the diversification of building materials suitable for specific applications, new materials, and an increased demand for better quality of construction.

Job-site mortar technology was and is not able to adequately meet all these requirements. As a practical consequence the development of the modern construction and building chemical industry in the countries of the Western world from the 1960s onwards was influenced mainly by three important trends, which can be seen nowadays worldwide:

- Replacement of the job-site-mixed mortars by premixed and prepacked dry-mix mortars.
- Mechanization of mortar application, including bulk transportation systems (e.g., silos), mechanical systems for automatic mixing of dry-mix mortar with water, and machine application (spraying) of wet mortar.
- Modification of mortars with polymer binders (redispersible powders) and special additives (e.g., cellulose ethers) and admixes to improve product quality and to meet the requirements of the modern building industry.

The introduction of dry-mix mortar technology and the use of silo transport and machine application of mortars made it possible that from 1960 to 1995 the volume of render and plaster mortar application in Germany increased by 600 %, while the number of employees in this sector decreased by 25 %, that means, productivity increased by 800 % [1].

Advantages of Dry-Mix Mortars

In job-site mixing technology, for each

building application a specific ratio of cement and fillers is mixed appropriately before being gauged with water, and the wet mortar is applied. The quality of such a mortar depends on the quality of the raw materials, their correct mixing ratio, the homogeneity of the mixture, and the consistency of the fresh mortar. Under these conditions the quality of mortars produced by job-site mix technology can not be guaranteed. The main disadvantages of job-site-mixed mortars are that the whole process cannot be automated, and the producer and applicator of a job-site-mixed mortar can not give a warranty to customers and end users due to a high risk of inconsistent quality of the prepared mortars. In addition, additives can either not be added or can only be added with a high risk of dosage and mixing errors and of obtaining inhomogeneous mixtures. The possibilities for producing specialized and individual products with job-site technology are very limited. Last but not least, handling and the logistics of job-site-mixed mortars are more complicated, and their applications are very limited.

In contrast to construction-site mortars, the modern dry-mix mortars are produced in a dry-mix mortar plant by mixing together all necessary ingredients such as binders, aggregates, and chemical additives. In this way different kinds of dry-mix mortars with well-defined product characteristics that correspond to the requirements for specific applications can be produced. The use of premixed and prepacked dry-mix mortars not only increases significantly production performance and the productivity on construction sites, but also guarantees a high degree of application safety and reliability in avoiding on-site mixing errors. Prepacked dry-mix mortars produced in a dry-mix plant assure that binders, aggregates, and additives of high and constant quality are mixed exactly in the same ratio, thus ensuring a consistent high level of quality [2], [3].

The raw materials used for the production of prepacked dry-mix mortars can be classified as follows:

(1) Mineral binders
- a) Portland cement (OPC)
- b) High-alumina cement (HAC)
- c) Special cements
- d) Hydrated lime
- e) Gypsum
- f) Anhydrite

(2) Polymer binder (redispersible powder)

(3) Aggregates, fillers
- a) Silica sands
- b) Limestone sand
- c) Dolomite sand
- d) Marble sand
- e) Lightweight fillers
- f) Special and functional fillers

(4) Additives
- a) Cellulose ethers
- b) Pigments
- c) Defoaming agents
- d) Air-entraining agents
- e) Retarding agents
- f) Accelerators
- g) Thickening agents
- h) Hydrophobing agents
- i) Plasticising agents
- j) Superplasticiser

The main applications of dry-mix mortars can be classified as in the following:

(1) High-volume products (ca. 70 % of total dry-mix mortar volume produced)
- Masonry mortars
- Base renders (cement- and gypsum-based)
- Bricklaying mortars
- Bricklaying adhesives
- Cement-based screeds
- Gypsum-based screeds
- Dry concrete
- Shotcrete concrete
- Mineral plasters

(2) Specialised products (ca. 30 % of total dry-mix mortar volume produced)
- Ceramic-tile adhesives
- Building adhesives
- Tile grouts
- Grouts
- Decorative mineral plasters
- Powder paints
- External thermal composite insulation systems
- Trowelling compounds
- Flooring compounds
- Repair mortars

The two different approaches to produce fresh, wet mortars ready for application either as a job-site mixed mortar (process A) or as a factory-made prepacked dry-mix mortar (process B) have major consequences for handling and productivity, as exemplified for base-render application in *Table 1*.

The application of high-volume dry-mix mortar was strongly promoted by the development of bulk transportation containers (silo systems) and mechanical systems for gauging the mortars with water and pumping for mechanical application by spraying. Compared to the manual gauging of dry-mix mortars delivered in bags to the job site (process B), the use of automatic gauging and pumping devices for the mechanical application of the mortar leads to an additional improvement in productivity (process D).

The handling of dry-mix mortars in bags could be eliminated for many high-consumption applications by filling the dry-mix mortars produced in the dry-mix plant into containers 1 – 20 m³ in volume

Table 1. Comparison of production, transport, and application of job-site-mixed mortars and dry-mix mortars

Process *	**A**	**B**	**C**	**D**
Transport of sand and cement separately to the job-site	+			
Manual mixing of the mineral binder and the aggregates on the job site	+			
Transport of the prepacked dry-mix mortar in bags to the job site		+	+	
Transport of the prepacked dry-mix mortar in silos to the job site				+
Manual mixing of the mortar with water	+	+		
Manual application of the wet mortar	+	+		
Machine mixing of the dry-mix mortar with water and machine spray application			+	+
Productivity (m 2 per man shift) for a render application	10	25	40	50 – 60

* A: completely manual method (job-site mixing technique); B, C, D: dry-mix mortar production in a dry-mix plant with different methods of transport and application.

which are transported to the site. With appropriate conveying systems the dry mortar is transferred directly from the silo into the attached mixing and pumping unit, where it is gauged automatically with water and pumped for spraying.

Combining the transportation of the dry-mix mortar in silos or containers with automatic gauging, pumping, and mechanical application of the mortar provides a further improvement in productivity (process D). In addition to the improved productivity, the automatic mechanical gauging and spraying of dry-mix mortars ensures consistency in handling and application of these products. Possible errors such as over - or underdosage of water or incorrect composition of the mortars are eliminated, which is especially important if less experienced or unskilled workers are working on the job site.

In Western Europe the consequences of this development were phenomenal. Since the 1960s a huge number of modern dry mortar plants have been established with millions of tonnes of capacity. In Germany, for example, nowadays approximately 100 dry mortar plants exist, producing 10 x 10^6 t/a of dry-mix mortars. There was a tremendous boom in dry-mix mortar technology after reunification of Germany after 1990, which now continues in the countries of Eastern Europe. The average growth rate for dry-mix mortar applications in Europe is approximately 12 % per annum, based on a production of about 35 – 40 x 10^6 t/a in 2000 [4].

Composition

Dry mortars are generally composed at least of three components: a binder, an aggregate, and additives.

Modern dry mortars are composed of many more components than those which were mixed directly on the site in the past. Today the simplest formulations are masonry mortars, brick-laying mortars, and low-quality tile adhesives, while highly sophisticated and high-performance dry mortars like self-leveling floor underlayments and decorative plasters may contain up to 20 ingredients. In this article the word aggregates is used for all types of mineral ingredients which do not have a binder function, even if they are added in small amounts like mineral ingredients with special functions, e.g., functional fibers or pigments. Other ingredients with small addition rates (redispersible powders) are treated as organic binders, although many others describe them as additives. The effect of using redispersible powders, especially in tile adhesives, shows clearly that they have a binder function. On the other hand, methyl cellulose, a multipurpose additive, is described in the chapter on additives although it also has a certain binder effect. In this case the binder effect does not play the major role.

Binders

The binder glues aggregates and other particles together and provides adhesion to the substrate. Due to their physical or chemical reaction binders play the major role for the final strength of the mortar. Binders can be classified as hydraulic and nonhydraulic binders. The former also set under water.

The setting reaction of the binders cement and hydrate lime occurs by chemical reaction. Cement reacts on contact with water during mixing while hydrate lime (without hydraulic portions) sets by reaction with atmospheric carbon dioxide. Gypsum and organic binders set physically: gypsum by recrystallisation with water and formation of matted crystal needles, and organic binders by forming a homogeneous polymer film.

- **Mineral Binders**

Cement (see also —› Cement and Concrete). In dry mortars ordinary portland cement (OPC) is mainly used. The hydration reaction leads primarily to the formation of calcium silicate hydrates, which retain their strength and stability even under water (hydraulic binder). While the quality of an OPC like CEMI 32.5R (for nomenclature, see DIN 1164 [5]) is sufficient for brick-laying mortars, masonry cement, renders, and many plasters, in tile adhesives higher qualities like CEMI 42.5R or CEM I 52.5R are desired. Dry mortars that are both mortars and decorative finishes, such as decorative plasters and tile grouts, mostly contain white portland cement. Fast-setting high-alumina cement (e.g., Fondue Lafarge) consists mainly of calcium aluminates and is used for dry mortars that require fast-setting properties or high-temperature stability.

Gypsum [6] (see also —› Calcium Sulfate). Calcium sulfate hemihydrate and anhydrite both set with water by forming calcium sulfate dihydrate. Calcium sulfate hemihydrate exists in two crystalline forms (depending on the production process): the α - form with larger crystals, higher tensile and compressive strength, and lower water demand, and the more amorphous β - form with high porosity and lower tensile and compressive strength and an up to three times higher water demand.

Anhydrite exists in two application-relevant phases: the anhydrite II phase, which is of importance in anhydrite-based screeds and the anhydrite III phase, which is a part of the multiphase gypsum used for plasters. Gypsum plasters contain β - hemihydrate as well as anhydrite II and III. Gypsum-based joint filler contains β - semihydrate.

Hydrated Lime (see also —› Lime and Limestone), [7]. Hydrated lime sets by reaction with carbon dioxide to form calcium carbonate and is therefore not a hydraulic binder. Hydraulic properties in some hydrated lime result from impurities or added materials with pozzolanic properties. For centuries hydrated lime was by far the most important binder in mortars. Today it is largely substituted by hydraulic binders, which set faster, but it is still in use, mainly because of its plastic properties. The workability of many dry mortars is improved by adding 5 – 30 wt % hydrated lime to the cement. Limes (including powdered hydrated lime) for building purposes are specified in DIN EN 459 [8].

- **Organic Binders**

Improving the characteristics of a cementitious mortar with organic materials is well known. In antiquity, for example, proteins in the form of liquid milk or even blood were used. In most modern applications, mortars unmodified by organic polymer binders are no longer able to meet state-of-the art technical requirements. Even cementitious mortars that contain cellulose ethers as an additive to improve their water-retention capability and workability characteristics adhere poorly, or not at all, to many of the materials used in the modern construction industry (e.g., polystyrene, cement fiber and wood panel; non-absorbent substrates like old tiles and fully vitrified tiles). Furthermore, cementitious mortars are very hard, brittle, and inflexible materials, but for many applications flexible and deformable cementitious mortars must be used. Thus, for many applications in the modern construction industry the modification of cementitious mortars with polymers today is a must. In two-binder systems, the mineral binder cement and the polymer binder in the form of a redispersible powder complement each other ideally. Their combination results in outstanding synergistic properties and characteristics of the dry-mix mortar which cannot be produced by either of the two individual binders alone.

In the early 1930s water-based liquid dispersions [9] were added prior to or together with the gauging water if required. Mortars which are modified in this way are referred to as two-pack ystems (powder-form mineral binder plus liquid polymer binder in a second pack). However, in practice many faults occurred with the use of the two-pack (or two-component) systems at the construction site. The main difficulty is the precise dosing of the polymer dispersion in its liquid form.

Dosing errors may occur due to insufficient knowledge, experience, and training of workers concerning the appropriate dosage for a specific application with precise requirements, or due to incorrect dosage, which may happen unintentionally by error or even intentionally to save on short-term costs. Incorrect dosage of the liquid polymer dispersion will change the characteristics and the technical performance of the mortar significantly, and this will lead to severe damages in various construction materials, e.g., through insufficient adhesive bond strength, flexibility and/or durability. Other reasons that argue against two-pack systems, apart from the difficult and risky handling, are the additional expenses and logistics difficulties (e.g., the need for additional containers and their subsequent disposal, storage and transport of liquid dispersions which could freeze or deteriorate by microbiological attack, more time consuming and ponderous handling on the job site with the two-pack system).

The invention of redispersible powders (trade name Vinnapas® Redispersible Powder) by Wacker Chemie in 1953 made possible the production of the first polymer-modified dry-mix mortars, known today as one-pack or one-component systems. Redispersible powders are polymer binding agents produced by spray-drying special water-based dispersions, mostly based on vinyl acetate – ethylene copolymers. These are often also referred to as redispersible powders [10], [11], because after mixing or redispersion with water, these powder polymer binders can be returned to their original water-based dispersion with all their typical characteristics and functions as polymer binders. The polymer film acting as a binder is formed after partial evaporation of the water by coalescence of the individual polymer particles. This polymer film acts as an organic binder, gluing together the filler particles, reinforcing the mortar structure and providing an excellent adhesion at the mortar – substrate interface. Polymer films in a cement mortar are shown in *Figure 1*.

The use of factory-made dry-mix mortars with precisely stipulated proportions for cement, aggregates, additives, and redispersible powders as organic binder results in a high-quality product with a high degree of application safety by avoiding possible errors during dosing and mixing at the construction site.

The modification of dry-mix mortars with re dispersible polymer powders improves, depending on the dosage, the adhesive bond strength on all kind of substrates, the flexibility and deformability of the mortars, the flexural strength, and the abrasion resistance, the toughness, the cohesion and the density (impermeability) of the mortar as well as the water retentivity and the workability characteristics. In addition special redispersible powders with a hydrophobing effect can result in a strong water-repellent effect of the mortars.

Aggregates

The majority of aggregates are normal size fractions of quartz, limestone, or dolomite. To adjust the grain-size distribution (see Section on *Testing*) normally different granulometric fractions of aggregates are necessary. Additionally decorative fractions of special granulometries like calcite, marble, jurassic limestone, or mica are used, mainly for decorative plasters. To reduce the density of a dry mortar and to increase the insulation effect lightweight aggregates like perlite, vermiculite, glass foam, expanded clay, and pumice are used as additional aggregates. Because of their low density (typically 80 – 500 kg/m^3) only few per cent by weight is added to the mix. Dry mortars for decorative renders or tile grouts are often colored with pigments.

Additives

Without additives modern dry mortars would not exist and many technical properties could not be achieved. Relative to the mineral ingredients the content of additives typically lies between 0.1 and 10 wt %. The additives are of organic or inorganic origin, often of polymeric nature. They can improve the mixing of the dry mortar with water, the properties of the wet mortar such as rheological behavior or the workability as well as the

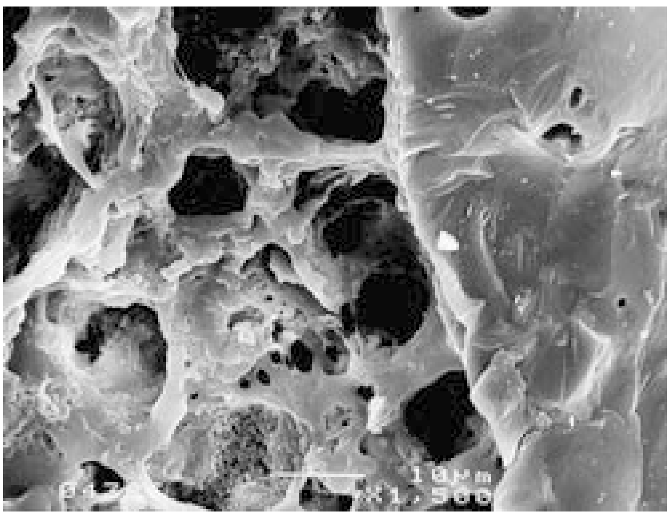

Figure 1. Scanning electron micrograph (x 1500; Wacker Polymer Systems) of the interface between a polymer-modified ceramic-tile adhesive (left) on a porcelain tile (right). The polymer films at the interface between the surface of the porcelain tile and the cementitious mortar can be seen clearly.

properties of the set mortar including the setting behavior.

- **Cellulose Ethers** [12]

Cellulose ethers are used as thickening and water retaining agents in dry mortars. Cellulose ethers are of major importance as additives, even though their addition rate is very low (normally 0.02 – 0.7 %). Out of all additives cellulose ethers together with redispersible powders cause the largest range of effects in dry mortars. The mainly used cellulose ethers in dry mortars are methyl hydroxyethyl cellulose (MHEC) and methyl hydroxypropyl cellulose (MHPC). Together they have a market share in dry mortars of at least 90%. Colloquially they are still called "methyl cellulose" or "MC", although pure methyl cellulose today has a very small market share. Other technically relevant cellulose ethers with a small share in the dry-mortar market are ethyl hydroxyethyl cellulose (EHEC) and hydroxyethyl cellulose (HEC). As (sodium) carboxymethyl cellulose is not stable in the presence of calcium ions, it is used only in few applications as a thickener.

The following sections cover relevant properties of MHEC and MHPC. As these properties are valid for both products, here they are simply referred to as MC.

Formation of Solutions and Wet Mortar Mixes; Viscosity Buildup. MC is water-soluble on a large temperature range. The most suitable MC's for dry mixes are powders whereby 20 – 60 wt % of the particles have a size smaller than 63 µm. The dry mix, in which MC particles are dispersed between binder and aggregate particles, avoids the formation of lumps which occurs only if powders are poured directly into water. Coarse MC products, normally classified as granular materials, are easy to dissolve in water without lump formation, but their slow dissolution makes them unfavorable for dry mortar mixes. For dry mortars with a neutral pH it should be considered that the granulometry is not the only parameter deciding the solution behavior of the MC. Some MC-grades are covered with a chemical crosslinking agent ("retarded solubility"), which causes particles to dissolve quickly only under alkaline conditions (e.g., coming from cement or hydrated lime). The alkalinity leads to an immediate breakdown of the crosslinking as well as to a fast dissolution of the MC in the mortar. Originally MC grades with retarded solubility were not developed for dry mortar, however, they have eventually spread to the dry mortar market.

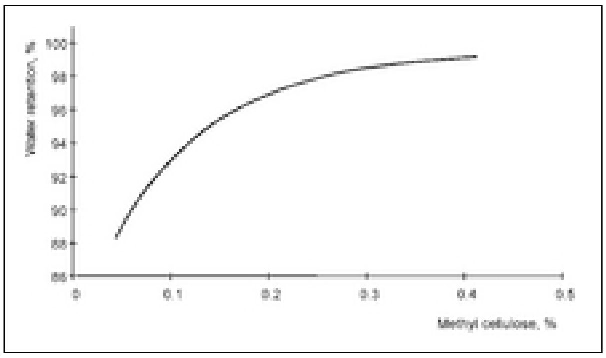

Figure 2. Water retention of a wet mortar as a function of the concentration of the added methyl cellulose (Walocel MKX 30 000 PP 01, Wolff Cellulosics, viscosity 30 000 mPa s, measured with a Haake Rotovisko)

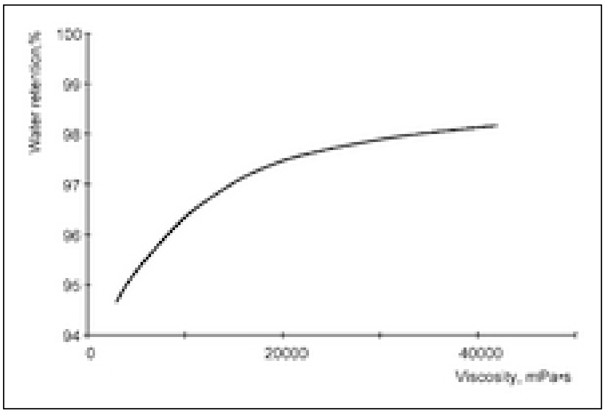

Figure 3. Water retention of a wet mortar as a function of the viscosity of methyl cellulose (2 % solution, 20°C, shear rate: D= 2.5 s^{-1}, measured with a Haake Rotovisko)

In pure solution and in a wet mortar, MC builds up a certain viscosity. The differences between low and high viscosities can be seen easily in a 2 % aqueous solution. Many MCs are specified by their viscosity measured at this concentration. The viscosities of such solutions varies between aqueous (viscosity up to a few hundred millipascals) up to jellylike (viscosity of several thousand millipascals). Different MC producers use different methods and apparatus to specify the viscosity of their MCs: the Haake Rotovisko, H¨ oppler, Ubbelohde, and Brookfield methods are mainly in use. The results of viscosity measurements on the same sample can differ by up to several hundred per cent between two methods, and this should be borne in mind when comparing viscosities of MCs from different producers.

Stickiness and Workability. Stickiness is an expression mainly used in the leveling of plasters and renders. Here "stickiness" means the feeling of adhesion that the worker experiences to be between the leveling tool and the wall. High stickiness requires more force during leveling and results in a lower workability. Both properties can be influenced by the MC.

Water Retention. The water retention value (WRV) of a mineral plaster is the percentage of water that remains in the plaster after capillary dewatering by an absorbant substrate (DIN 18555, part 7) [13].

Cement and gypsum-based mortars need water for setting, and this water must be retained in the mortar for a longer period of time. The thickness of thick-bed mortars widely used in the past (normally in the range of centimeters) protected the mortars from drying out too fast after coming into contact with water absorbing substrates, the sun, or other environmental conditions like wind, dry air, or a high ambient temperature. Today, wall materials with high capillary forces are used (e.g., aveated light weight concrete), and the thickness of mortar layers generally has decreased. MC is necessary to retain the water during the setting reaction. The high water retention of a modern dry mortar is mainly due to MC. *Figures 2* and *3* show an example of the water retention of a wet mortar as a function of concentration and viscosity, respectively, of the added MC.

For the measurement of water retention see Section on *Testing*.

Water Demand and Yield. A mortar requires a certain consistency which is well known to skilled workers. They add as much water as is necessary to get the right consistency. The water demand depends on the ingredients and their addition rate in the formulation. MC is the main factor which influences the water demand. Mainly the viscosity, the addition rate, and the additional thickening effect of MC are the parameters. The water demand (water-solid-factor) influences also the yield of a mortar. It is measured in liters of wet mortar per 100 kg of dry mortar and is an important parameter for the efficiency of lightweight plasters. Some MC producers supply special MCs which guarantees high yields in the mortar. This can help to reduce the amount of lightweight aggregates.

Other properties which can be influenced with MCs are open time and tensile adhesion strength of a tile adhesive as well as the slip resistance of a tile in the mortar (see Section on *Testing*), the rheological properties, plastification, and lubrication.

- **Other Additives**

Starch Ethers. Mainly hydroxypropyl starches are added to plasters. Despite their low viscosities (mainly 100 – 500 mPa s in 2 % solution) they distinctly increase the viscosity of mortars when added to MC-containing mortars. Typical addition rates are between 0.01 and 0.04 % in cement-based renders and plasters, and 0.02 – 0.06 % in gypsum-based plasters. The water demand of the plaster is slightly increased, and this is associated with a slightly higher yield. The water retention of the mortar is not increased. With regard to the workability the sagging of the wet mortar from vertical walls and supports is reduced. At the optimum dosage the workabilities are improved.

Air-entraining agents act physically by en-training air micropores in the mortar. This leads to a decreased wet mortar density, a better workability, and a higher wet mortar yield. The included air leads to better insulation against cold and heat, but also to lower strength. Air-entraining agents are based on powder form and mainly sodium salts of fatty acid sulfonates and sulfates. The addition rates in plasters and masonry mortars normally varies from 0.01 to 0.06 %. The optimum addition rates can be found by monitoring the air content of the mortar and its workability.

Accelerators. Accelerating systems are used in large amounts in cement-based systems to adjust the desired setting properties. In particular calcium formate (e.g., Mebofix® , Bayer, Leverkusen, Germany) or lithium carbonate (e.g., from Chemetall, Frankfurt, Ger-many) are used successfully. The addition rate is up to 0.7% for calcium formate, and up to 0.2 % for lithium carbonate.

Retarders. The main application for retarders are gypsum plasters and gypsum-based joint fillers. Without retardation the setting of gypsum is too fast. Different retarders are used, mainly salts of fruit acids like tartaric or citric acid and of synthetic acids (e.g., Retardan® grades, from Tricosal, Illertissen, Germany). The typical dosage lies between 0.05 and 0.25 %.

Hydrophobic agents (water-repellent agents) prevent water from penetrating into the mortar, but the mortar remains still open for water vapor diffusion. The performance of hydrophobic agents can be measured by the capillary water absorption (DIN 52617) [14]. The main applications for hydrophobic agents are cement-based plasters for exterior application, mineral waterproofing slurries and tile grout. There are two groups of hydrophobic agents on the market: metal salts of fatty acids. (e.g., zinc stearate or sodium oleate, e.g., from Greven Fettchemie, Bad M¨unstereifel, Germany), and polymeric redispersible powders with hydrophobic properties (some Vinnapas® grades, Wacker Polymer Systems, Burghausen, Germany). The first group has the advantage of lower addition rate (0.1 – 1 %), the second one the advantage of significantly better durability, because hydrophobic redispersible powders are not washed out of the plaster by rain even after years. Additionally, the use of hydrophobic redispersible powders does not lead to wetting problems during mixing the dry mortar with water and it improves the adhesion of the cured mortar to the substrate (see Section on *Organic Binder*).

Superplasticisers have a strong influence on the water demand of a mortar. A mortar containing superplasticisers requires less water than usual to get the same consistency. Consequently, an unchanged water demand leads to a lowering of the consistency. The effect of superplastification is explained by the model [15] that different surface charges of the cement particles lead to the inclusion of water when they agglomerate. By the adsorption of the super-plasticiser, the surfaces are discharged and water is set free. Depending on legal restrictions and technical advantages casein (many producers) or synthetic superplasticisers are used, e.g., on the basis of sulfonates of lignin, naphthalene, melamine – formaldehyde condensates, or polyether carboxylates. Examples of producers are SKW (Trostberg, Germany), Sika (Switzerland), and Perstorp (Sweden). Superplastisisers are mainly used in mortars which need very good self-leveling properties like self-leveling floor underlayments, screeds, and pourable flooring tile adhesives. The dosage normally lies in the range of 0.2 – 1 %.

Fibers can be distinguished into two groups: long fibers are mainly used for reinforcement of mortars. Short fibers (e.g., Arbocel and Lignocel grades from J. Rettenmaier & S¨ohne, Ellwangen-Holzm¨uhle, Germany) are used in influence wet-mortar properties and water demand.

Defoamers reduce the air content in wet mortars (e.g., Agitan P products from M¨unzing Chemie, Heilbronn, Germany). Powder defoamers on a different chemical basis (mainly hydrocarbons, polyglycols or polysiloxanes on an inorganic carrier) are in use.

Production

Production, storage, transport, and quality control of dry-mix mortars are defined in DIN 18557 [16].

Modern dry-mix plants (*Figure 4*) with a production capacity of typically 40 000 to 250 000 t/a mostly are built on a small area because the production line is oriented vertically, and the silos for the raw materials are placed above the mixing unit.

After appropriate quality control, the raw materials are transported by the receiving

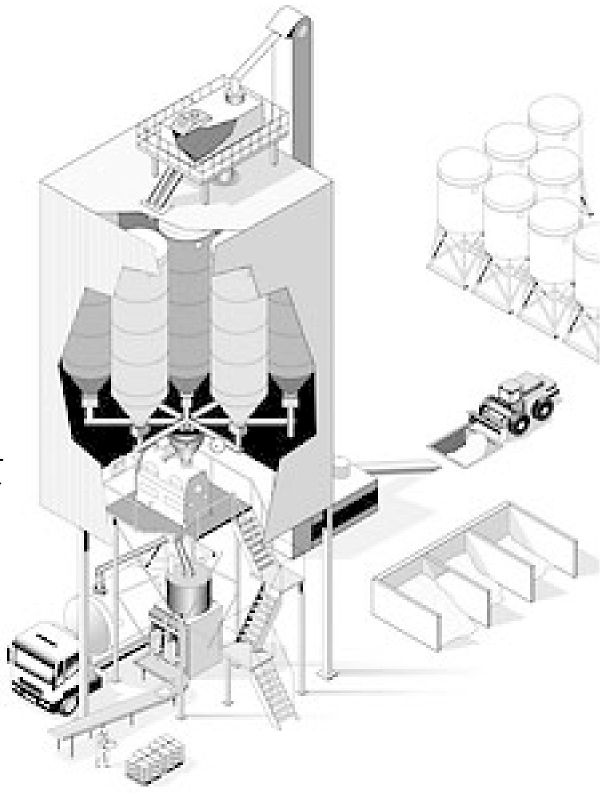

Figure 4. Schematic diagram of a dry-mix mortar plant (m-tec, Neuenburg, Germany)

Figure 5. Typical dry-mix mortar plant (m-tec, Neuenburg,Germany)

system to the different silos at the top of the plant. Consequently, the material flow is mainly gravitational, which saves on investment and running costs. The raw materials are transferred by gravity or by appropriate conveying systems (disk feeders, dosing screws, pneumatically) into the high-accuracy hopperscales weighing system. Controlled by the fully automated electronic control system, the mixing unit is filled with all raw materials needed for each formulation for a specific dry-mix mortar. As mixing unit mostly special mixers are used which are suitable for the whole product range of dry-mix mortars (from fine-particle materials up to coarse dry mortars). Such mixing units, available in a wide variety of different sizes and designs, allow short batch cycle times and fast, homogeneous mixing. The temperature of the dry-mix materials should not exceed 50°C during the whole mixing process to avoid deteriorating the thermoplastic and sensitive additives. After a short mixing process of about 3 – 10 min for highly efficient modern mixing units, the homogeneous dry-mix mortar is discharged into the intermediate finished-product storage silo. After quality control, the dry-mix mortar is discharged into transport silos or transferred to bagging and palletising units, ready for the transport to the construction site. *Figure 5* shows a typical dry-mix mortar plant.

In the production of dry-mix mortars, the quality of all raw materials used, especially the bulk mineral materials, must be controlled according to the national standards (e.g., EN 196 for cements). If aggregates like silica quartz sands are not available in the appropriate quality, the dry-mix mortar plant must include installations for grinding, washing, drying, and classification into different sieve fractions. The residual humidity of all fillers should not be higher than 0.3 %, and the temperature of the sand after the drying process should not exceed 60°C before being used. The sieve curve within the different filler fractions should be constant without large variations (e.g., by combining several subfractions).

The design, the size and the number of silos for all raw materials and the design of the whole mixing and packaging unit depends on the raw materials available and the number, types, and volume of different dry-mix mortars to be produced in the dry-mix mortar plant. For all gypsum-based products usually a separate production line is used to avoid contact or mixing of cement-based products with gypsum.

Testing

Consistency. Applying a mortar to a support requires to mix it with a certain amount of water. Skilled building workers instinctively mix the dry mortar with the amount of water which leads to the desired application consistency. A higher or lower amount of water leads to undesired properties. The required amount of water for mixing is described by the term w/s (water to solid ratio).

During the development of a dry mortar the w/s values should be adjusted to a consistency which will probably be used also on building sites. If formulations with different addition rates of additives or different additives are compared, it is generally worthless to compare formulations with the same w/s, because nearly all additives change the consistency or the w/s slightly. To find a way of controlling the consistency and to compare different formulations, several testing procedures exist. The consistency of mortars, renders, and plasters is checked by the slump method, which is done in a similar way as in the concrete industry (—› Cement and Concrete, Chap. 2.4.1.). The standards DIN 1168, part 2 (only for gypsum-based products) [17], DIN EN 13279, part 2 [18], and DIN 18555, part 2 (for mortars with mineral binders) [13], define the slump to be "the diameter in millimeters of a pat made of a mixture of water and building plaster and formed by vertical blows after removal from the mold and jolting of the mixture" [13]. The consistency of more liquid products like self-leveling floor screeds or pourable flooring tile adhesive can be determined by the diameter of flow. This procedure does not require jolting. The consistency of a tile adhesive can be controlled by viscosity.

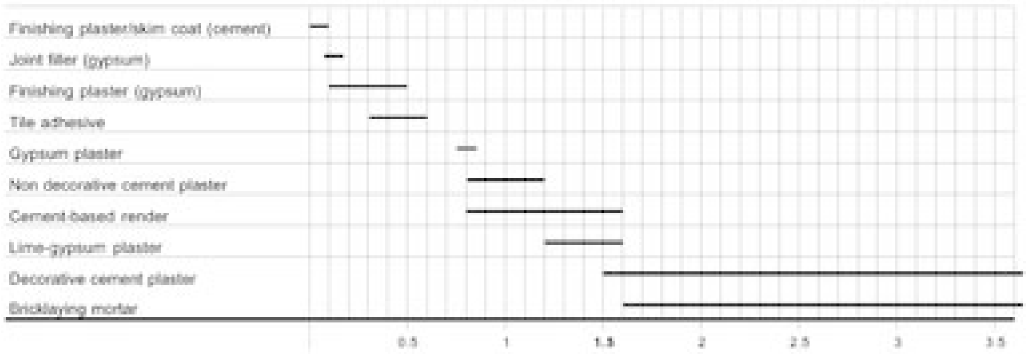

Figure 6. Maximum grain size of some European mortars

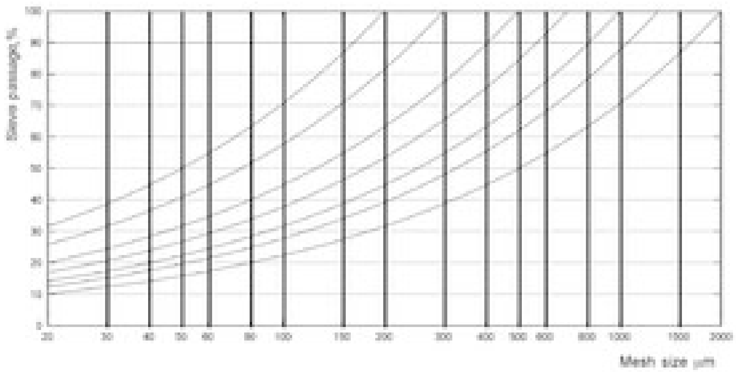

Figure 7. Reference curves calculated from the Fuller equation

Water Retention. The standard DIN 18555, part 7 [13] describes the measurement of water retention. The water-absorbing wall is simulated by water-absorbing filter plates. The test is carried out on a plaster with a consistency as used in practice. The wet mortar is spread onto filter plates. After a certain time the water amount absorbed by the filter plates is weighed. Than the water retention is calculated in %. Different kinds of mortars require different water-retention values for good application properties.

Setting Time. The setting behavior of gypsum-based building plasters is determined by the Vicat needle test according to DIN EN 13279, part 2 and DIN 1168, part 2. [17], [18]: "The start of setting of building plasters containing additives is indicated by the time in minutes after which a Vicat needle, in the course of a penetration test into a plaster sample, comes to a standstill at a specified height." The time is calculated from the commencement of moistening of the building plaster with water. Coarser systems such as cement renders and plasters are less suitable for the Vicat testing procedure.

Air content. Freshly mixed mortars contain pores, one origin of them being air entraining agents, another being adsorbed air on the surface of the particles. DIN 18555 part 2 [13] describes a method to determine the total amount of air pores in a fresh mortar. It is an integral method which does not give any indication about the size or the distribution of the pores. "The air content of fresh mortar shall be measured by the pressure method using a preset test apparatus with a capacity of 1 dm 3 . The test apparatus shall have a pressure chamber in which a defined pressure is produced. By opening an overflow valve a pressure balance is affected between the pressure chamber and the sample container (measuring vessel) which is filled with fresh mortar. The drop in pressure is a measure of the air content in the fresh mortar." [13]

Granulometric analysis mainly is done with screen sizing. The residues on the test sieves are weighed and expressed as a percentage of the initial weight. Plotting the diameter of the particles as a function of the percentage sieve passage gives the individual granulometric curve. The curve has a specific shape for each dry mortar. The coursness of dry mortars also varies (*Figure 6*). The granulometric range of most dry mortars varies between 0.1 and 4 mm. In some mortars a high wet mortar density is necessary to lead to high compressive strengths. In such cases the granulometric distribution of all mineral components should be optimised accordingly. To use a simple picture, the spaces between the bigger particles should be filled by smaller particles to give the best space filling. This best distribution of diameters of particles can be calculated and plotted as a Fuller curve (*Figure 7*).

Open Time. In the colloquial speech used on the building sites "open time" is a general expression for the length of time in which a freshly mixed mortar can be applied. The expression "open time" mainly is used for applying tile adhesives, sometimes also for plastering and rendering. A more precise definition of "open time" is given in the following three definitions: The former DIN 18156 (part 2) defines the "open time" to be the time between the application of the mortar layer and the formation of a skin. The skin formation can only be tested qualitatively with a wad of cotton. Another testing procedure defines the "open time" as the time after which the wetting of the back of the tile is at least 50 % of the square of the tile. Nowadays European laboratories are testing the open time mainly according to EN1346 [19]. Here the open time (in minutes) is the largest time range after which the necessary tensile strength of a tile adhesive according to EN 12004 is reached. The tested times are 5, 10, 20, and 30 min.

Slip Resistance. A tile adhesive should have a good slip resistance mainly for the following two reasons: for tiling with heavy tiles like marble tiles, and second for countries where the tiling of a wall starts from the top (as in Germany) and not at the bottom. In the latter case the lower tile supports the upper tile and prevents it from slipping down.

The slip resistance is measured with a standard tile of size 10 x 10 cm and a weight of 200 g on a concrete slab according to EN 1308 [20].

Tensile adhesion strength is an important property of many dry mortars. For tile adhesives EN 1348 [21] specifies four conditions of storage: standard storage under standard climatic conditions for 28 d, after water immersion, after freeze – thaw cycle, and after heat aging storage.

Applications

Brick-Laying Mortars and Related Adhesives

Brick-laying mortars are used to join all kinds of bricks: red clay bricks with low water absorption, strongly absorbing sand-lime bricks, and aerated light weight concrete. Generally, bricks with low water retention applied in thick layers require mortars with low water retention, while smooth and even bricks with high water absorption require a mortar with high water retention applied in thin layers. *Table 2* lists the different formulations.

DIN 18555, parts 1 – 9 [13] describes the testing of mortars with mineral binders. Most of them are valid for brick-laying mortars as well as for cement-based renders and gypsum plasters.

Renders and Plasters

Plaster is defined in DIN 18550, part 1 as "a coating of plaster mortar or coating materials applied to walls and ceilings in one or more layers in a specified thickness,

Table 2. Typical formulations of a brick-laying mortar and an aerated light weight concrete adhesive (in parts by weight)

Component	Brick-laying mortar	Aerated light weight concrete adhesive
Cement (e.g., CEMI 32.5R)	12 – 20	36
Hydrated lime	0 – 6	4
Limestone dust, 0 – 0.1 mm	10 – 20	
Quartz or limestone sand, 0 – 4 mm	60 – 80	
Quartz sand, 0 – 0.5 mm		60
Air-entraining agent	0.01 – 0.03	
Methyl cellulose, medium viscosity	0.02 – 0.04	
Methyl cellulose, high viscosity		0.3 – 0.4

which does not acquire its final characteristics until it has set on the building component" [22]. Different types of dry mortar render and plaster are classified on the basis of the type of binder used:

- Plaster and render mortar with mineral binders (cement, gypsum, and possibly hydrated lime)
- Decorative plaster mortar with cement, redispersible powder, and possibly hydrated lime as the binder (see Section on *Testing*)

Dry mortar render and plaster with other binders like potassium silicate, redispersible powder as the sole binder, hydrated lime as the sole binder, and clay are not covered here. Plasters assume a range of physical tasks, for instance, protection against weathering or chemical or mechanical actions. Weathering means the ingress of moisture or fluctuations in temperature. In addition plasters have to confer adequate protection against driving rain, but they are used also for bathrooms and other rooms where moisture occurs. Cement or lime – cement plasters are used to satisfy these requirements.

Render and plaster must have good water vapor permeability and be suitable for painting and hanging heavy papers. Mineral renders, typically applied in a single layer with a thickness of ca. 10 – 30 mm, also serve as a uniform and smooth substrate or load-bearing layer for subsequent finishing coating materials like ceramic tiles, paints, and decorative finishing coatings. Cement-based renders are used for exterior applications and wet rooms, whereas gypsum-based renders are used exclusively for interior walls.

Nowadays, in most European countries (not in the UK) machine-applied render/plaster is much more common than manually applied render or plaster. Accordingly, the render/plaster for machine application must fulfill the additional requirements of a very rapid development of consistency and high water retention. Both parameters are steered by choosing the appropriate grade of methyl cellulose. Next to the trend to machine application, there is a tendency to use more lightweight plasters.

Cement and Lime – Cement Renders. The main requirements for cement and lime – cement renders are high non-sag properties during application, easy workability, low stickiness to the leveling tool, and crack-free setting. To fullfill these requirements, the formulation requires the optimum concerning granulometry and the addition of additives like methyl cellulose, starch ethers, and air-entraining agents. *Table 3* lists typical formulations of a lime cement render and of a lightweight render based on cement.

Gypsum Plasters (—› Calcium Sulfate). As the working steps necessary for a gypsum plaster are more complicated and time-consuming than for a cement render, the typical formulations are also more complicated. The main focus is always on the correct adjustment of the setting retardation, which enables the worker to finish all steps of the work before the surface sets or becomes dry. As the working traditions are different in many countries, the local formulations always have to be adjusted to the different working procedures. A main difference in working concerns the final working steps after the second leveling. In central Europe the surface is wetted with water and a cream is rubbed out of the surface with a sponge, followed by the smoothening with a knife, which results in extremely

Table 3. Typical formulations of a standard lime – cement render and a lightweight cement render (in parts by weight)

Component	Lime – cement render	Lightweight cement render
Portland cement CEMI 32.5R	8 – 12	18 – 25
Hydrated lime	6 – 8	0 – 5
Quartz sand, 0.2 – 0.8 mm	80 – 85	
Limestone sand		60 – 75
Limestone dust		5 – 7
Expanded polystyrene		1 – 2
Starch ether		0.01 – 0.02
Hydrophobic agent	0.15 – 0.25	0.1 – 0.2
Air-entraining agent	0.015 – 0.03	0.03 – 0.05
Methyl cellulose, viscosity 15 000 mPa s	0.08 – 0.12	0.1 – 0.12

smooth surfaces. In southern Europe and Great Britain, watering of the surface is avoided, and this leads to a coarser surface. To obtain the desired smoothness, the surface is plastered with a fine-grained top coat.

Lightweight gypsum plasters containing perlite or vermiculite are very common. Especially in these formulations methyl cellulose plays an important role in increasing the yield and saving on the cost of the lightweight aggregates. In a lightweight gypsum plaster for machine application the right MC allows 100 – 200 L of perlite to be saved per tonne of plaster for the same coverage compared to a MC without any additional thickening effect. Such an MC will yield to an approximately 10 % higher coverage of the plaster mortar.

The true yield of a machine-applied lightweight plaster can be measured only in a plaster spraying trial. Typical German gypsum plasters have yields in the range of 80 L/100 kg of dry mortar for a gypsum – lime plaster, and up to 120 L/ 100 kg of dry mortar for machine- applied gypsum lightweight plaster.

Relevant standards are draft DIN EN 13279, parts 1 and 2 [18] (formerly DIN 1168, parts 1 and 2).

Table 4 shows typical formulations of a gypsum plaster, a gypsum – lime plaster, and a lightweight gypsum plaster.

Textured Mineral Finishing Plasters. Mineral finishing plasters, stuccos, putties, and skim coats are part of a coating system and are applied usually on a thick-layer base coat (render) or on other types of uniform and smooth surfaces (concrete, plasterboard, etc.). For exterior walls, mainly lime – cement plasters are used as a decorative finishing material. Finishing plasters must provide the facade with an optically attractive surface finish and have to fulfill physical functions such as a durable protection of the covered wall areas and undercoats against dampness and weathering.

To meet their required physical functions over long periods, mineral finishing coating materials for exterior application must have a good adhesion to the substrate, a low water absorption and a high water-repellent effect (low coefficient of water-absorption), good drying characteristics (good water-vapor permeability), and low susceptibility to cracking; the modulus of elasticity of the mineral coating should be lower than the modulus of elasticity of the layers below it.

These requirements are met in an exemplary manner by mineral-textured finishing plasters produced as factory made dry-mix mortars. The term "finishing plaster" nowadays refers to facade-coating materials pigmented in white or light pastel colors which are used as the final surface finish without any additional painting being necessary. Mineral finishing plasters are composed of hydrated lime and cement as mineral binders, aggregates (fillers), pigments, and additives such as cellulose ethers and starch ethers to improve the water retention and processing. If required, other additives such as air entrainers, water-repellent agents, retarders, and fibers are added. The ratio of cement and hydrated lime can be varied according to the different requirements; the higher the cement content the higher the compressive strength, the toughness, and the water resistance, but there is also a higher risk of crack formation due to the brittleness and shrinkage of the mortar. The higher the content of hydrated lime, the better the workability, and the lower the compressive strength. Carbonate fillers such as marble or limestone can be used additionally or even exclusively instead of silica sands. The technical performance of the finishing plaster can be improved significantly by the addition of organic polymer binders in the form of redispersible powders. The different structures of the hardened mortar originate from a different particle size distribution of the fillers used in the formulation (structure-giving large grains) and from the application method

Table 4. Typical formulations of a gypsum plaster, a gypsum – lime plaster, and a lightweight gypsum plaster (in parts per weight)

Component	Gypsum plaster	Gypsum – lime plaster	Gypsum lightweight plaster
Gypsum	74 – 98	40 – 50	70 – 100
Limestone		20 – 35	
Hydrated lime	1.5 – 5	15 – 20	2 – 5
Perlite		0.3 – 0.8	3 – 5
Starch ether	0.01 – 0.04	0.01 – 0.03	0.01 – 0.05
Air-entraining agent	0.015 – 0.03	0.015 – 0.03	0.01 – 0.03
Setting retarder	0.025 – 0.05	0.025 – 0.04	0.025 – 0.04
Methyl cellulose, viscosity 30 000 mPa s	0.16 – 0.23	0.16 – 0.23	
Methyl cellulose for high yield			0.2 – 0.24

(application by spraying, brush, trowel, roller, etc.). Mineral finishing plaster is applied manually but nowadays increasingly by machine spraying.

The standard DIN 18550 [22] defines the technical requirements and the application of mineral base renders as well as of the finishing plaster coating systems.

Tile Adhesives

Ceramic wall cladding for building interiors and exteriors is by no mean a new invention. The first ceramic wall cladding materials in the form of fresco and mosaic tiles were produced ca. 3500 years ago in Egypt, Persia, and China. Tiles provide an esthetically attractive decorative surface in combination with important functional benefits, being water resistant, tough, long-lasting, hygienic, and easy to clean. For these reasons tiles are important floor and wall covering materials in the construction industry. In 1999 ca. 4.5 x 10^9 m^2 were produced and laid worldwide. The most important market was Asia (1.9 x 10^9 m^2) followed by Europe (10^9 m^2) and America (0.9 x 10^9 m^2).

Mainly earthenware tiles for indoor applications (non-frost-resistant porous tiles with a water absorption of ca. 25 % according to the EN 87 [23] and frost-resistant stoneware tiles (non-porous tiles with a water absorption of ca. 1 %) for indoor and outdoor applications are used. Different types of natural stones are installed for indoor and outdoor applications. Nowadays, the hard-pressed fully vitrified tiles (porcelain tiles) with an extremely low water absorption (<0.1 %) and an excellent scratch, wear, and weather resistance, as well as glass tiles, are being increasingly used, mainly for outdoor applications and for floors. In addition there is a strong trend to use tiles in larger sizes (large-formatted tile, up to 40 x 40 cm).

Ceramic tiles and natural stones previously were exclusively laid with the thick-bed mortar technique based on job-site-mixed mortars. In this method, sand and cement are mixed together on the job site to produce a simple cement mortar with a cement/sand ratio of ca. 1/4 to 1/5. After applying (buttering) this mortar on the reverse side of the water-(pre)soaked or prewetted tile in a thickness of 15 – 30 mm, the tile buttered with the mortar is pressed to the prewetted surface to be tiled. The tiles are tapped to ensure uniform flatness of the tile surface, and thus a final mortar bed of 10 – 25 mm is obtained. This procedure not only causes a compaction of the mortar, but leads in addition to the migration of the fine cement particles into the porous reverse side of the tiles and into the porous substrate. In this way a mechanical fixation or anchoring of the tile in the mortar bed is assured, as well as anchoring of the mortar on the substrate after curing of the cement. Because this simple type of mortar has no slip resistance, tiling must be started at the bottom, and spacers must be used to obtain regular joints between the tiles.

However this method is a very time-, cost- and, material-consuming process which requires experienced craftsmen. They have to decide whether the substrate and the tiles are suitable for using this method, a certain soaking time of the tiles is required depending on their porosity, the mortar must be mixed in the correct ratio and consistency, and the right amount of mortar has to be applied on the reverse side of the tile before it is laid. More significantly, there are a lot of technical restrictions in using this technique in the modern building industry. For example, only porous and relatively small format tiles can be laid on porous, solid, and strong mineral surfaces (backgrounds) with this method due to the need for mechanical anchoring of the mortar.

Therefore, the thin-bed mortar technique today has replaced the thick-bed mortar method in most industrialised countries. After the polymer-modified prepacked dry-mix mortar has been gauged with water, it can be applied to a large area of the surface to be tiled with a notched trowel (floating technique) to give a ribbed mortar bed of uniform thickness. Due to the good water retention capacity of the thin-bed mortar (effect of cellulose ether), neither the tiles nor the substrate (background) have to be presoaked or prewetted. The tiles are then pressed into the mortar bed with a slightly twisting action. If the adhesive mortar is formulated in the appropriate way by using adequate additives, tiles that have just been laid in the fresh mortar bed will not slip. Thus, the insertion of spacers between the tiles is not necessary and

Figure 8. Application of a thin-bed ceramic tile adhesive (spreading the adhesive mortar with a notched trowel on a wall to be covered with ceramic tiles); picture: Wacker Polymer Systems

tiling can be carried out from the top to the bottom. This technique creates an adhesive mortar bed of ca. 2 – 4 mm thickness, depending on the dimensions of the trowel notches used (usually 6 x 6 x 6 mm, depending on the size of the tiles and the flatness of the substrate). The thin-bed mortar technique is thus more cost-effective than its thick-bed counterpart. It also uses less material, can be applied more universally, and its execution is simpler, faster, and safer. This is even true in cases where the background is uneven and has to be coated or levelled with an equalisation mortar first.

With this thin-bed technique (*Figure 8*) using specially designed prepacked dry-mix adhesive mortars, all technical demands of modern building industry using different types of backgrounds and covering materials under different and extreme climatic conditions can be satisfied. Today there is wide range of ceramic-tile adhesives available, depending on the substrate to be tiled and the tiles being used: standard and flexible, normal- and fast-setting, as well as special adhesives such as white mortars for fixing natural stones, waterproofing adhesives, flow-bed mortars for floor tiling, gypsum-based adhesives, and high-flexibility mortars for fresh screeds.

Dry-mix mortars for thin-bed tiling must fulfill technical requirements such as good workability characteristics, good water-retention capability, long open time and adjustability time even at high temperatures, and good non-sag properties. After curing, the cement-based adhesive mortar must provide a good adhesive and cohesive bond strength

Table 5. Typical formulations for ceramic-tile adhesives

Adhesive type *	A	B
Portland cement (OPC)	45	35
Silica sand (0.05 – 0.5 mm)	53.1 – 51.6	59.6 – 57.6
Cellulose ether (viscosity ca 40 000 mPa s)	0.4	0.3
Redispersible powder	0 – 4	5 – 10
Additives (if required for special performance)	(0 – 5) (0 – 5)	

* Type A = standard polymer-modified ceramic-tile adhesive,
Type B = flexible, high-quality, polymer-modified ceramic-tile adhesive.

between all types of covering materials (e.g., natural stones and all kind of ceramic tiles) and various backgrounds (e.g., concrete surfaces, brickwork, lime – cement renders and base coats, gypsum, wood, old tile surfaces, gypsum wallboards, aerated lightweight concrete, particle boards, etc.). This must be guaranteed even after exposure to frost, dampness, and even permanent immersion in water. In addition to good adhesion, the thin-bed adhesive mortar must have sufficient flexibility to absorb and reduce possible tensions between the background and the tiles caused by different thermal expansion co-efficients of the covering materials and the sub-strates as well as possible movements of the background.

These overall characteristics of a thin-bed adhesive mortar can only be achieved by prepacked polymer-modified cementitious dry-mix mortars containing cellulose ethers as additives and redispersible powders as a polymer binding agent. Typical basic formulations for a standard and a high quality flexible ceramic tile adhesive are given in *Table 5*.

The most important technical requirements in Europe for a ceramic tile adhesive (besides workability) and the test methods are summarised in *Table 6*.

Tile Grouts

Tile grouts are used to fill the joints between tiles or natural stones laid on walls or floors. Cement-based tile grouts with appropriate formulations are suitable for interior and for exterior application. In combination with the tiles they must provide an optically attractive surface and must perform physical functions. The tile grout must be capable of reducing stresses within the whole wall or floor covering material, it must protect the materials and layers under the tiled surface against mechanical damage and the negative influences of water penetrating into the whole construction. Thus a cementitious grout must have good adhesion to the edges of the tiles, low shrinkage, sufficient deformability or flexibility, high abrasion resistance, good toughness and cohesion, low water absorption, and an excellent workability (low stickiness of the wet mortar). According to their application, two main types of tile grouts can be classified (*Table 7*).

For white and colored tile grouts, white cement is used as a mineral binder. Alkali-resistant pigments such as iron oxides should be used for colored grouts. Appropriate carbonate fillers can be used additionally or even exclusively instead of silica sand as a filler. To reduce the risk of efflorescence, the use of hydrophobing agents is very helpful, and microsilica or trass can additionally be added. The main technical requirements for tile grouts are summarised in *Table 8*.

Exterior Thermal Insulation Composite Systems

External thermal insulation composite systems (ETICS) or external insulation and finishing systems (EIFS) were developed in Europe in the early 1970s. The first oil crisis in Germany in 1973, together with financial support from the government for homeowners, helped tremendously to promote the system. From 1973 to 1993 ca. 300 x 10^6 m^2 of facades in the Federal Republic of Germany were equipped with ETICS [24], and more than 18 x 10^9 L of heating oil was thus saved. Apart from saving energy, emissions of pollutants and CO_2 are reduced.

ETICS also significantly increases the comfort while living in a building due to a more constant temperature and humidity over the seasons. It reduces significantly building damages by decreasing the temperature variations in the external wall construction and combined with less condensation of dampness allows to

Table 6. Summary of European standards for ceramic-tile adhesives

Test	Standard	Requirements
Definitions and terminology	EN 1322	
Slip resistance	EN 1308	<0.5 mm
Wetting capability	EN 1347	
Tensile adhesion strength	EN 1348	Minimum requirement: >0.5 N/mm 2 for all storage conditions
Storage conditions:		Additional requirement: >1.0 N/mm 2 for all storage conditions
standard conditions: 28 d sc*		
water immersion: 7 d sc + 21 d in water		
heat aging: 14 d sc + 14 d 70°C + 1 d sc		
freeze-thaw: 7 d sc + 21 d in water + 25 cycles freeze-thaw		
Heat-aging test: 14 d sc + 14 d 70°C + 1 d sc		
Freeze – thaw resistance: 7 d sc + 21 d in water + 25 cycles feeze – thaw)		
Open time	EN 1346	>20 min; or >30 min
Deformability/flexibility with transverse deformation test	EN 12002	
Adhesives for tiles – definitions and specifications	EN 12004	

* sc: 23°C/50 % R.H.

Table 7. Typical formulations for tile grouts

Tile grout type *	A	B
Portland cement	25 – 30	20 – 25
High-alumina cement (HAC)	0 – 10	0 – 10
Pigments (TiO2; iron oxides)	0 – 5	
Filler (silica sand and/or carbonate filler)	75 – 56.9	79 – 51.9
Cellulose ether	0 – 0.1	0 – 0.1
Redispersible powder	0 – 2	1 – 5
Additives for workability	0 – 1	0 – 3

* A: standard gray tile grout for interior and exterior use, B: high-quality, pigmented, smooth-surface tile grout for interior and exterior use.

reduce the overall building costs. Therefore, thermal insulation is not only a sensible investment in new buildings, but also a good renovation measure, especially if the facade has to be renovated anyway.

The first ETICS, introduced in the 1970s, consisted of a dispersion-bound paste adhesive to which cement was added at the construction site. This compound was used to fix expanded polystyrene panels to the walls to be insulated. The same product and procedure was used to embed the fiberglass mesh that serves as a re-inforcement in the reinforcement layer or base coat on top of the fixed thermal insulation panel. In earlier years mainly dispersion-bound synthetic resin plasters were applied as a finishing coat after the base coat had been primed.

However, in practice many mistakes occurred when using this system, in particular during the mixing of the dispersion-bound paste adhesive with cement at the construction site. With this system it is not possible to always produce a homogeneous mixture with a constant polymer to cement ratio, and adhesives and base coats with different compositions are thus obtained. This results in inadequate product characteristics and possible damage to the facades due to insufficient adhesive bond strength or flexibility. This argument also apply to the two-component systems, in which a water-based dispersion is added to dry-mix mortars at the construction site. For these reasons, together with the above-mentioned principle disadvantages of two-pack systems, today the polymer-modified cement based dry-mix mortars have almost completely substituted all other systems for ETICS.

Classic ETICS consist of the following components:

- Adhesive for fixing the thermal insulation panels, mainly expanded polystyrene, on the wall (depending on instructions and technical guidelines, additional mechanical fixing with special dowels may be necessary).
- Base-coat for embedding the reinforcement mesh on top of the thermal insulation panels (mechanical protection of the thermal insulation panels).
- Mineral finishing coating (mainly cementitious plasters or stucco with different structures).

A typical formulation (in wt %) for the adhesive and base-coat mortar is given in the following:

Portland cement	20 – 30
Filler (silica sand and/or carbonate filler, 0.05 – 0.5 mm)	64.7 – 75.9
Cellulose ether	0.1 – 0.3
Redispersible powder	4 – 5
Additives	0 – 3

The combination of individual components of an ETICS must always be seen as a whole.

Thus the adhesive, thermal insulation panels, embedding mortar, fiber mesh, primer (or key-coat if necessary), dowels (if an additional mechanical fixing is required), and the finishing coat must be carefully adjusted to each other and must be tested and approved together as a system. Therefore, it is not permitted to combine individual components from different sources to create an ETICS which has not been tested and approved as a whole system. *Figure 9* shows a typical composition of a ETICS.

To meet the technical requirements, ca. 4 – 5 % of organic binder in form of a redispersible powder is used for the adhesive mortar and the base coat. This means that apart from the required good adhesion of the cementitious mortar on

Table 8. Important requirements, test methods, and standards for cement based tile grout mortars

	Standard	Requirements
Grouts for tiles – definitions and specifications	prEN 13888	
Determination of water absorption	prEN 12808-5	water absorption (WA) determined with 16 x 4 x 4 cm prisms; requirements: fundamental characteristic: WA after 30 min <5 g; WA after 240 min <10 g additional characteristic: WA after 30 min <2 g; WA after 240 min <5 g
Determination of resistance to abrasion	prEN 12808-2	abrasion tester according to EN102; requirements: fundamental characteristic: volume removed during test <2000 mm 3 additional characteristic: volume removed during test <1000 mm 3
Determination of shrinkage	prEN 12808-4	shrinkage determined with 16 x 4 x 4 cm prisms after 28 d sc; requirement: <2 mm/m
Determination of flexural and compressive strength	prEN 12808-3	flexural (FS) and compressive strength (CS) determined with 16 x 4 x 4 cm prisms after 28 d sc and freeze – thaw cycles; requirements: FS >3.5 N/mm 2 ; CS >15 N/mm 2

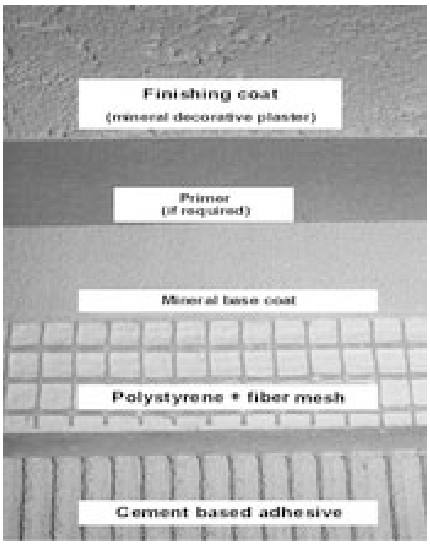

Figure 9. Typical components of a ETICS (Wacker Polymer Systems)

the substrate and on the insulating polystyrene panels, a sufficient deformability (flexibility) and a high degree of impact resistance of the mortars are achieved as well.

A large choice of different materials and systems are available nowadays as finishing coats for the ETICS. Apart from the classic dispersion-bound plasters, available in many structural variations and colors, mainly mineral cement – lime plasters or stuccoes, silicate plasters, and to a certain extent silicone resin plasters are used.

Various countries have differing regulations and specifications for ETICS. At present a European standard is being prepared for external thermal insulation composite systems [draft from European Organisation for Technical Approvals (EOTA)]. It will describe all specifications for the individual components of the system and the overall composite system itself (e.g., physical and construction specifications as well as techical requirements like water absorption, behavior under hydrothermal stress, inflammability, water-vapor permeability, adhesive strength, impact resistance, etc.).

Worldwide, new thermal insulation regulations(e.g., WschVO in Germany [25]) furthermore establish minimum requirements for the K-value (thermal insulation value) of the external walls of new buildings. For concrete and bricks walls these binding minimum requirements can often only be met by the additional application of an ETICS, and this will lead to a further growth in thermal insultation systems. Even in countries with a high average temperature, thermal insulation composite systems are becoming popular for saving energy for air-conditioning.

Powder Paints

The use of liquid dispersion paints is well known and has proven itself in practice since their invention in the 1950s, and today this is the leading technology for interior and exterior paint application. As a sole binding agent for this type of products aqueous dispersions based on styrene – acrylate, vinyl acetate ethylene, or other copolymers are used.

In DIN 55945 surface coating materials such as laquers and paints are defined, classified, and characterised. Paints according to this standard are compounds in liquid and pasty form, based on solvents, binding agents, pigments, fillers, and additives, but including powder-form coating materials as well. Paints can be classified as:

- Solvent-based coating materials
- Water-based coating materials (laquers, paints)
- Spray-applied powder coatings
- Paints and coating materials in powder form (powder paints) to be mixed with water before application

Powder paints were known for many decades before the invention of the liquid dispersion paints. In the early days of the powder paints the binder was either of organic origin (e.g., distemper paint based on glue) or of inorganic origin (e.g., mineral paints based on the mineral binders hydrated lime and/or cement). For a long time the mineral binder was modified with organic binding agents (casein, cellulose ether, starch ether) to improve the technical characteristics of the mineral coating material.

Natural organic binders have since been replaced with much more efficient synthetic polymer binders in the form of redispersible powders, and this has again led to an increasing importanceof powder paints. Redispersible powder as organic binder is used as the sole binder in powder dispersion paints and for the modification of mineral powder paints based on cement, hydrated lime, or water glass (silicate powder paints) to improve their technical performance and durability. Powder dispersion paints were first used on building facades in Austria in the 1960s and later in Germany. They provide almost the same characteristics as liquid dispersion paints, but offer all the advantages of a powder system.

Powder dispersion paints are used for interior and exterior applications. The most important difference in formulation is the content of polymer binder. The higher the polymer content, the better the adhesion and the higher the wet-scrub resistance of the paint.

Like typical dry-mix mortars, powder paints are supplied in paper bags or in silos to the job site and are gauged with water before use and are applied by brush, roller or spraying.

Table 9 summarises the most important standards and technical requirements for powder paints.

Cementitious Waterproofing Sealing Slurries

Water in liquid or in vapor form is the most destructive weathering element for

Table 9. Important test methods and standards for (powder) paints

	Standard	Comments
Definitions General requirements	DIN 55945 DIN 53778	definitions, composition, types of painting materials, general requirements concerning workability, capability of dilution, tinting, compatibility with pigments, minimum temperature of application, recoatability, gloss, hiding power
Water absorption	EN ISO 15148	coefficient of water absorption W <0.5 kg m^2 $h^{0.5}$ and *W* S_d <0.2 kg $mh^{0.5}$ for exterior application (EN ISO 15148 substitutes DIN 52617)
Water-vapor permeability	EN ISO 12572	diffusion-equivalent air-layer thickness S_d <2 m (EN ISO 12572 substitutes DIN 52615)
Wet-scrub resistance	DIN 53778	>1500 cycles for indoor application, >5000 cycles for outdoor application and for scrub-resistant paints

building materials such as concrete, masonry, and natural stones.

Traditional sealing and waterproofing systems (e.g., according to DIN 18195) include bituminous materials, plastic waterproofing foils, and metal tapes for interior and exterior applications. Different types of materials can be used to seal and protect the surface of buildings or their structural components against the intrusion of dampness and water. Nowadays products for this purpose are based on reactive resins like epoxy and/or polyurethane, dispersions (paintable waterproofing membranes), and mineral binders like cement, which are known as waterproofing membranes or sealing slurries.

Cementitious waterproofing membranes have been successfully used for more than 40 years in Europe. The structures to be protected were either exposed to periodic or long-term wetting (surface water, seepage water), low hydrostatic pressure (soil dampness), or in combination with appropriate engineering even high hydrostatic pressure. Cementitious membranes (slurries) are used to waterproof wet rooms and water tanks, and due to their excellent weathering resistance also for exterior surface protection. Further typical applications are the sealing and waterproofing of basement walls, of swimming pools, as well as walls and floors in bathrooms, and on balconies and terraces as a waterproofing layer to be tiled over. Some of the main advantages of cement-based waterproofing membranes are their excellent resistance to water (even if exposed permanently), excellent long-term weathering resistance, good scratch resistance, good load-carrying capacity and much higher water-vapor permeability than most of the other systems.

Figure 10 shows a typical application of a cementitious waterproofing sealing slurry by brush.

Cement-based waterproofing slurries are easy to use, nontoxic, provide a fully bound and monolithic surface without joints, and can be easily applied on substrates with complex surface shapes. In contrast to other systems, cementitious waterproofing slurries can even be used on damp and wet mineral surfaces. Their physical properties are also less temperature-dependent compared to bitumen-based materials. So far there are no standards available for these alternative sealing products, but national guidelines of mortar associations are well accepted in the building industry [26].

Simple, non-polymer-modified cement-based slurries are still used for protection against surface water, but they are not suitable for sealing against water under hydrostatic pressure. To improve the poor adhesion, the poor water tightness, and the extremely low deformability and flexibility of these unmodified systems, the polymers are added in the form of liquid dispersions on the job site or as a redispersible powder already mixed with the dry-mix mortar. Special additives in these dry mix mortars include water-retention agents, thickening agents, and rheological additives.

Today standard or rigid mineral waterproofing slurries are polymer-modified, prepacked dry-mix mortars with a high cement and relatively low polymer (redispersible powder) content. They are used for mineral substrates which are dimensionally stable, sound, and solid without risk of crack formation, movement, or dimensional changes such as shrinkage. Developments in the late 1970s led in Europe to flexible waterproofing slurries, which to a certain extent are capable of bridging small cracks (up to ca. 1 mm) in the substrate.

Figure 10. Typical application of a cementitious water-proofing sealing slurry by brush (Wacker Polymer Systems)

The flexibility of such products strongly depends on the polymer to cement ratio and on the flexibility of the polymer itself. Flexible and highly flexible waterproofing cementitious slurries are used on substrates that are still subject to shrinkage, vibration, movement, stress, and crack formation, and on substrates that are difficult to coat, such as wood, steel, aerated lightweight blocks, and gypsum. Due to their high polymer content (up to 40 wt % of the total formulation), they have a high diffusion resistance and are chemically resistant to chloride, sulfate ions, carbon dioxide, or other aggressive substances. In central Europe flexible cementitious waterproofing sealing slurries represent the last domain for two-component (two-pack) systems, which are based on prepacked dry-mix mortar and liquid admixes. However, even in these high-polymer products, there is a strong trend towards one-pack systems in form of polymer-modified dry-mix mortars.

Self-Leveling Underlayments and Screeds

Self-leveling underlayments (SLUs) are from a technical perspective probably the most complex field for dry-mix mortars. On a given uneven substrate (i.e., screed or surface to be refurbished), self-leveling mortars have to provide a suitable, smooth and solid substrate for applying all kinds of flooring materials like carpets, wooden parquet, PVC, tiles, etc. Self-leveling underlayments should be applicable in an easy and efficient manner, even for large areas. Therefore, the SLU material has to have very good flow characteristics, and self-leveling and self-smoothing properties. In addition, it should set and dry quickly so that the flooring material can be applied on top of the hardened mortar after only a few hours. The SLU mortar should adhere to all kinds of substrates and exhibit low shrinkage, high compressive strength, and good abrasion resistance.

The technical requirements for SLUs range from very simple to highly sophisticated products. They vary in thickness from a very thin layer of 1 – 10 mm (feather finish, self-leveling/troweling mortars and underlays), up to 60 mm for self-leveling screeds, which are always applied by machines (mixing and pumping in one set up).

The screeds are used as a load wearing base in a thickness from 30 to 80 mm, and are thus high-volume-application mortars. These mortars can be based on cement or gypsum (anhydrite) as mineral binder, the latter providing underlayments with a high dimensional stability (low or even no shrinkage). The set time ("walk-over time") of these materials varies from normal/regular setting to fast-setting products. Normally this depends on the requirements of a specific job, that is, the flooring material can be laid on the SLU in a certain time frame. The shorter the setting and drying time, and the thicker the mortar is applied, the more complicated and expensive the formulation becomes. Self-leveling compounds for underlayments and screeds are based on special hydraulic binders like Portland cement (OPC), high-alumina cement (HAC), and gypsum (anhydrite), to achieve fast curing and drying by avoiding excessive shrinkage or expansion.

So far there are no standards on self-leveling underlayments (SLU) in Europe. However, the technique and its application have been well known for many years, and exclusively polymer-modified prepacked dry-mix mortars are used for this application.

Patching and Repair Mortars

Concrete is a very versatile, long-lasting, and durable building and construction material if it is applied according to the state of the art.

In the past, and even today, unfortunately, repeated disregard of the fundamental principles of concrete and structural concrete application still leads to severe and serious damage in the building industry. The cost of the repair of concrete structures has dramatically increased over the last 30 years in all industrial countries. In Germany approximately 20 % of the cost of the volume of structural concrete work is attributed to the repair and maintenance of existing buildings and structures. The degradation of structural concrete is caused by corrosion of the steel reinforcement due to carbonation of concrete caused by atmospheric carbon dioxide and other aggressive media (e.g., SO2 , acid rain). The corroded steel reinforcement increases in volume and splits off the overlying concrete, thus destroying the structure.

In the construction industry concrete repair work can be classified into two types:

1) Repair of concrete which does not contain steel reinforcement and which does not have load-bearing functions. It is normally carried out for aesthetic reasons (cosmetic repair work) only, with patching mortars or patching compounds.

2) Repair and reconstruction of damaged reinforced and load-bearing concrete structures to maintain and reconstitute their structural stability and function. This is carried out in stages with different kind of mortars, which are part of a "concrete rehabilitation system" (typical applications: repair work and rehabilitation of bridges, parking decks, tunnels, etc).

Patching mortars for reprofiling and cosmetic repair are based on dry-mix mortars. Usually cement-based mortars are used for indoor and outdoor applications, whereas gypsum-based products are only used for some specific indoor applications (cosmetic repair), i.e., for filling small holes, voids, cracks and cavities to restore the original dimensions.

To guarantee the durable and reliable repair of structural concrete, concrete rehabilitation systems must restore the corrosion protection of the steel reinforcement (alkaline environment), reprofile the concrete structure, restore its load-bearing functions, and finally restore the protection and thus durability of the whole construction (protection against weathering and environmental damage caused by CO2 , SO2 , Cl2 , deicing salts, etc).

For the rehabilitation of structural concrete three types of mortars are used today: cement-based concrete mortars (CC; mostly applied as a shotcrete mortar), polymer (modified) cement concrete (PCC) as prepacked dry-mix mortars, and epoxy cement concrete (ECC).

Today mainly PCC mortars are used for the rehabilitation of concrete structures. These mortars can be applied by hand as well as by machine, in a wet or even a dry spraying shotcrete process. Different kind of mortars delivered as dry-mix mortars with different characteristics and functions are used as the components for concrete rehabilitation systems:

- Primer and adhesion promoter for the reinforced steel (polymer-modified cementitious slurry or epoxy-based coating materials)
- Adhesion-promoter slurry (primer or key-coat) for the concrete to be repaired (polymer-modified cement based slurry)
- Restoration and reprofiling mortar (polymer-modified cement-based mortar)
- Fine stopper or smoothing mortar (polymer-modified cement-based mortar containing fine aggregates)
- Protective and finishing coat (dispersion paints, crack overbridging paints, cementitious waterproofing sealing slurries, etc.).

So far mainly national guidelines implemented by various organisations and regulations are relevant to the requirements for concrete-repair systems [27]. Concrete rehabilitation systems are subjected to an official approval according to relevant laws and regular quality supervision from independent test institutes.

Market Aspects

Precise data on worldwide production and consumption of dry mortars are not available, although for Germany, France, and Italy calculations of the production are known. According to ref. [28] the production of dry mortars in 2001 was 10 x 10^6 in Germany, 3 x 10^6 in Italy, and 2.7 x 10^6 in France, and total consumption in Western Europe was 30 x 10^6 [28] or 35 – 40 x 10^6 according to other estimates. Worldwide consumption lies in the range of 50 – 60 x 10^6 [28], or (60 – 70) x 10^6 according to other estimates.

With increasing local working costs the ratio between dry mortars and mortars mixed on site is increasing, as the application of dry mortars requires less time for the same work. Worldwide dry mortar consumption is increasing. While growth was strong in central Europe from the 1960s to the 1980s, nowadays growth is mainly in Eastern and Southern Europe, as well as in parts of the Asian and Latin American market.

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