Use of metakaolins in comparison to silica fume in concretes

Comparison of metakaolin with other concrete admixtures e.g., silica fume - advantages and disadvantages

1. Chemical composition

High-quality metakaolins, such as the Metaver types, consist mainly of amorphous kaolin in addition to small amounts of quartz and traces of feldspars. These minor constituents are inert and do not react with the cement in concrete.
In the case of low-grade metakaolins, high proportions of feldspars lead by physical effects to high water demand, high superplasticizer quantities and consequently to low strengths.
The silica fume contains amorphous silicon dioxide as the main phase. In addition, the minor constituents are limited according to EN 13263 Part 1. Thus, according to paragraph 5.2.2, the proportion of elemental silicon must not exceed 0.4 wt.%, but this is always present due to the production process. Elemental silicon reacts with the cement (more precisely the Sodium hydroxide and potassium hydroxide) and forms hydrogen gas.
If some concrete contains 30 kg of silica fume per m^3 and if, for example, 0.3 wt.%, i.e., 90 g of elemental silicon, is present in this concrete, 72 litres of hydrogen are formed within 24 h (according to the ideal gas law). This volume reduces the density and thus the strengths. Hydrogen in concrete can lead to hydrogen embrittlement of the reinforcement, but this has not yet been documented.

2. Workability

2.1. Homogeneity during mixing

Practical experience shows that the mixing of silica fume in concretes always encounters challenges. Inhomogeneities occur in the hardened concrete. The only remedy is to use compacted silica fume. However, prices then rise by around 10 to 20 euro cents per kg of silica fume.
When using metakaolin, no challenges regarding inhomogeneities have been reported so far.

2.2. Mixing time and fresh concrete properties

Today, there are no concretes that do not require superplasticizers. Polycarboxylate ethers (PCE's) are now used almost exclusively. These PCE's consist of a "backbone" with negatively charged carboxylate ions (COO^-) and side chains of polyethers (R-O-R). The polycarboxylate ions are electrostatically bound to the surfaces ("plus to minus") and the long side chains brush past each other without hooking. The better the polycarboxylate ions adsorb to the surface of the solid particles, the better the effect. Since the surface of silica dust (only silica!) is negatively charged, adsorption occurs only to a limited extent. With metakaolin, which consists of silicon dioxide and aluminium oxide and has a positive surface charge, the PCE molecules are much more strongly bound to the surfaces.
This results in a much more effective action of the PCEs in metakaolin compared to silica dust. One gets a smoother flowing concrete with less use of superplasticizer. The flowability of concretes containing metakaolin is much higher and the willingness to deaerate much better than when silica fume is used. Less air leads to higher strengths. It is possible, depending on the formulation, to reduce the amount of superplasticizer. This saves costs and accelerates the concrete (high superplasticizer quantity retards!).
Thus, when using silica fume, just as with ground granulated blast furnace slag, you get a sticky slow-flowing concrete.

3. Reactivity

The range of concrete admixtures for the partial replacement of cement is vast. Type I (e.g., limestone powder) or type II (e.g., fly ash) concrete admixtures are used in the precast industry, but they reduce

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the cycle times of the production of skills due to the delay (only heating helps here). The demoulding times must be based on the course of the day. An extension of one or two hours therefore causes a halving of the cycle frequency; the formwork can then no longer be demoulded on the next day, but only on the day after next.
Metakaolin is the only concrete admixture that leads to an acceleration of the concrete. All other admixtures delay setting. Slender components lose the heat of hydration faster due to their unfavourable volume to surface ratio. Therefore, the effect is much more pronounced when Metakaolin is used compared to other admixtures, such as silica fume.

4. Strengths and deformation

When concrete admixtures are used to replace cement in concretes, an increase or decrease in strength is observed compared to zero concrete. This ratio, expressed mathematically as a pozzolanic index, can be used as a measure of the reactivity of the admixture. A safety deduction is added to this value by the authorities. From this, a so-called k-value was determined for each concrete admixture. Thus, limestone powder as concrete admixture type I has the value k = 0, fly ash and ground granulated blast furnace slag as type II have the value k = 0.4.
Good metakaolins and silica fume have a pozzolanic index of 115 to 125, and the creditable k value is 1. These two admixtures are thus the best.
Strength values are not the only important factor in evaluating a concrete. Concretes show increased shrinkage at elevated levels of calcium silicate hydrate (CSH) phases. Here, metakaolin has an advantage over silica fume because metakaolin also forms larger amounts of calcium aluminate phases (CAH phases), which are more stable against shrinkage.
Therefore, concretes with metakaolin show significantly lower cracking tendency than concretes with silica fume, resulting in significantly more durable components.

5. Durability and environmental influences

5.1. External influences

Concretes with metakaolin, like concretes with silica fume, have denser microstructures. This dense microstructure is formed from the reaction of calcium hydroxide with the silica fume and alumina. Without metakaolin, the cement matrix consists of 25 wt.% portlandite $Ca(OH)_2$ and weakens the cement structure. By using metakaolin, the concrete is protected against external attacks; chlorides, sulphates, carbon dioxide and other chemicals cannot easily penetrate the concrete.

5.2. Internal influences; alkali-silica reaction (ASR)

Not all aggregates are resistant to the influence of the cement matrix. The high pH value can lead to dissolution and crystallization processes in or on the aggregates. The higher the pH, the faster these reactions occur. These processes are always associated with an increase in volume and can destroy the concrete. The level of the pH is directly proportional to the alkali concentrations (sodium and potassium) in the pore solution of the concrete.
It is known that CSH phases can only incorporate small amounts of alkalis into their crystal lattice. When silica fume is used, the prevention of ASR is not possible.
When using metakaolin in concretes the formed CAH phases incorporate larger amounts of alkalis into their crystal lattice, thus reducing the concentration of alkalis in the pore solution and thus lowering the pH - damage to the aggregate does not occur.

5.3. Colour

Since high quality metakaolins are very bright, it is possible to produce concretes with the highest demands. In the case of fair-faced concrete with white cement, colour brighteners such as titanium dioxide can be completely dispensed with.
Silica powder contains elemental silicon and carbon as graphite during production. The concretes become very dark. Treated light grey silica powder is available on the market, but it is very expensive.
If an anthracite-coloured concrete is to be produced, the use of black silica powder is not recommended. The graphite is not stably integrated into the concrete matrix - the surface fades and you get a dirty grey concrete.

6. Example use of metakaolin in high-strength concrete

Picture 1 – 3: Production of concrete shells (4 cm thick) for an ice channel of a bobsleigh track.

Properties of the concrete:
Flow (Hägermann cone): 320 mm (thin concrete)
Self-compacting
Compressive strength: 110 – 120 MPa
Flexural strength: 12 MPa
XF3; XF4; XM3
Low shrinkage: 0.2 mm/m (50 d)

Compressive strength up to 160 MPa are possible (similar to MS)