SILICA FUME AS ADDITIVE TO THE CONCRETE USED FOR CONCRETE PAVEMENTS

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Abstract

The paper deals with silica fume as one of the most frequently used and most effective additives for improvement of mechanical and durability properties of concrete used in construction of concrete pavements. The use of mineral additives in general, and silica fume as well, is possible in two ways; as an additive to concrete during production and as an additive to concrete during batching. In order to get a comprehensive overview of concrete pavements, we shall present a division of concrete pavements and properties of concrete for concrete pavements.

Keywords: concrete, concrete pavement, cement, mineral additives, silica fume

1 Introduction

The first concrete pavements were made as a series of independent slabs. Later on, due to the load transfer, they were connected by shear studs [2]. The use of these concrete pavements dates back to the 19th century, and the first classical concrete pavement was made in the USA, in the State of Ohio in 1892 [7]. The first mechanically made concrete pavements in Europe were made in Germany, in 1924. Croatian marks the construction of the first concrete pavement in 1935 [6].
The practice worldwide is that concrete pavements are made equally, alongside with asphalt pavements for heavy traffic load. In France for example, concrete pavements are placed on new roads planned for heavy traffic load (airports), except in special circumstances, or for medium traffic loads with high frequency traffic (motorways).
Numerous important concrete properties are improved with the use of mineral additives, especially waste byproducts such as fly ash, blast furnace slag and silica fume. The influence of additives on the properties of concrete depends on the quantity of used additive, the ratio of concrete mixture, chemical additives such as superplasticisers and air-entraining agents, as well as on other factors [3].

2 Concrete pavement

2.1 Concrete pavements in general

Concrete (rigid) pavement structures consist of a concrete slab on a base made of stabilized and loose, mechanically compacted grained stone material. The most important part of the rigid pavement structure is the concrete slab. The base has no great significance in relation to the transfer of load, but it must be well made, to prevent its erosion during time, and thus appearance of voids, which would endanger the concrete slab.
Thickness of concrete slab is somewhere between 16 and 25cm. The cement stabilized base course is somewhere between 15 to 20cm thick and the loose part of the base is 20 to 40cm

thick. The modulus of elasticity of the concrete slab is significantly higher than the modulus of elasticity of the asphalt courses, thus the deflections of concrete slabs under load are much smaller than the deflections of flexible pavement structures. Concrete pavement structures distribute the load over a large surface area. These structures are flexible also, they bend under load and when the load is released they return to their original position. Long-term load causes fatigue in these structures which manifests itself in the appearance of cracks [8].

2.2 Concrete of the concrete pavement

There is a wrong belief prevailing in Croatia and in some professional circles as well, that the concrete of the concrete pavement is some kind of special concrete, specially sensitive and susceptible in the choice of its components, production and application. The concrete of concrete pavement is a plain structural concrete, the composition of which depends on the design properties and technology of placing (Fig. 1.).
The main characteristic in the choice of composition materials and in mix design is the reduction of shrinkage to the least possible amount, which is also a condition in mix design preparation of all sensitive reinforced concrete structures. In this sense the concrete should require as less water as possible, should not be to finely crushed, which is most frequently seen today, and should have approximately 35% of mineral additives which decrease its heat of hydration. The carbonate, volcanic crushed and alluvial proved to be a good aggregate. Aggregate with a harder grain, but not necessarily volcanic is required for surface courses.
A careful choice of air-entraining agents is the most significant and most serious problem, necessary to ensure sufficient resistance to frost and deicing salt. Mix design preparation of pavement concrete, its choice and efficiency tests require the outmost attention [6].

Figure 1 Concrete pavement in the placing stage

2.3 Composition of concrete used for concrete pavement

Taking into consideration its composition, Portland cement (strength class 32,5 or more) or mixed Portland cement with mineral additives is used in preparation of pavement slabs. Slag is mostly used in Croatia, in the amount of 25 – 50 % of slag as additive to cement since it is suitable for production of cement with low heat of hydration, which is used in placing of pavement structures. Fly ash is a byproduct of fuel combustion (coal) in thermal power stations. Fly ash particles, due to their small size and specific surface area (2000 – 4000 cm^2/g) are suitable for addition to cement after crushing. Silica fume is a byproduct of the reaction of high purity quartz and coal in electric furnaces during silicon production. Due to exceptional fineness of particles, with the increase of silica fume in concrete, the need for water also significantly increases. Precisely because of this the use of silica fume is restricted to 15 % in relation to cement.

Except these properties, the heat of hydration of cement is also very important. Heat is released by hydration of cement. The temperature maximum occurs 2 – 4 hours after the start of the setting process. Problems occur after the concrete reaches its maximum temperature and starts to cool. This is when the temperature stress transforms from compressive to tensile stress, i.e. in the area where the concrete is significantly weaker. This is why cement with low heat of hydration is used for concrete pavement. Cement with specific surface area of 325-375 m^2/kg is suitable for use in concrete pavements. By decreasing the percentage of Portland cement clinker and adding slag, fly ash or natural pozzolan to cement, the heat of hydration is decreased. As opposed to the silica fume, fly ash and slag do not increase the specific surface area of cement. Increase of specific surface area disrupts the water-cement factor which is in a linear relation to the extracted water quantity. A smaller quantity of extracted water is effective in the sense that it protects concrete from drying out when the concrete is susceptible to cracking due to plastic shrinkage, while excess water extraction can be harmful since it can create a course of low quality material at the concrete surface.

The quantity of cement in the concrete of pavement structures is usually somewhere between 300-400 kg/m^3. Generally, the cement content must be kept as low as possible, but with adequate strength and durability properties. Chemical additives are added to concrete in order to improve its properties, an not as some kind of "correction" of possible faults. Plasticizers, air-entraining agent and thickeners are most frequently added.

Natural aggregates or ones produced by crushing in quarries are most frequently used in concrete pavement structures. Certain faults in the aggregate can be improved by adequate concrete mix design. The aggregate must be made of healthy, good quality rock, with no impurities or admixtures. It must be mechanically solid and resistant to different environmental conditions (Fig. 2.). Especially important properties are its resistance to frost and thawing and resistance to deicing salt, as well as its resistance to wear, since these are the most significant negative environmental effects on a concrete pavement. Inadequate choice of aggregate is most often connected to damage on the concrete pavements caused by frost and thawing and the influence of deicing salt [7].

Figure 2 Surface of the concrete pavement

2.4 Types of concrete pavement structures – specific characteristics of the composition of concrete and means of placing

Main types of concrete pavement structures are:

- Classic (plain) concrete pavements

Classic concrete pavement is a rigid structure with no deformations or very small permanent deformations, meaning that the pavement rigidity is not influenced by high temperatures or large traffic loads. Traffic lanes of these pavements are constructed in different widths; they can be as wide as the pavement itself, a half of the pavement width or a part of the pavement width. Present day machinery enables the placing of concrete in widths of 11m and even wider. Concrete with rigid plastic consistency is used for this kind of pavements, placed by slipform concrete pavers with vibrators or slipform pavers with respective internal vibrators (Fig. 3).

Figure 3 Finishers

- Reinforced concrete pavements

These kinds of pavements are rarely executed, their main advantage being a significantly lower sensitivity to cracks and greater durability. Reinforcement helps to avoid creation of cracks and increases compactness between expansion joints. However, load bearing capacity of the pavement is not significantly increased since the percentage of reinforcement is very small. The concrete is the same as the one in classic concrete pavements.

- Infinitely reinforced concrete pavements

Advantage of these pavements is that they do not have expansion joints, so when cracks appear due to shrinkage, the reinforcement takes over all stress.

- Prestressed concrete pavements

This kind of pavement is primarily used for special surfaces, mostly on airports. It is not usually executed on motorways due to the specific equipment needed for transport and placing of concrete. The concrete must satisfy all requirements needed for production of precast elements, produced in a precast concrete plant.

- Rolled concrete pavements

Rolled concrete represents a new concept of transport, placing and compaction of concrete whose slump in fresh state is equal to zero. Rolled concrete has a rigid plastic consistency, consolidated by external vibrators. It differs from classic concrete by its consistency and the means of placing. To achieve efficient compaction, the concrete must be sufficiently dry to take over the weight of the vibrating equipment but it also must be sufficiently moist to allow the distribution of binder through the mass during the mixing and vibrating process.

Its application started during construction of forest roads, but it spread to airport platforms. Rolled concrete is used in pavement construction for greater load bearing capacity and lower prices as compared to asphalt. Aggregate takes up approximately 70 – 80 % of the mixture volume, and therefore can significantly influence the properties of fresh and hardened concrete. The most significant difference in aggregate of rolled and classic concrete is in the grain size composition of the mixture. Rolled concrete mixtures are less cohesive than the classic concrete mixtures due to a lesser water content, therefore attention must be given to aggregate segregation. Portland cement and pozzolan are almost always used as binder. Fly ash is used for pozzolan, in the amount of 25 to 40 % of the total binder volume. Concrete of these pavements is efficiently spread with the same machinery used in placing of asphalt pavements.

- Pavements with ultra thin concrete course

This course is usually made of fiber reinforced concrete of rapid increase in strength, thickness 5 to 10cm. This kind of composite pavement ensures a durable traffic surface but can also be used as a fast form of remediation of worn out asphalt pavements, because it enables the roads to be opened for traffic very soon after remediation due to the fast increase in strength of the concrete course. This kind of pavement can take large traffic loads without appearance of any kind of damage and ruts at the same time offering all the advantages as the classic concrete pavement.

- Pavements made of precast concrete blocks

Precast concrete blocks are used for pavements and surfaces in areas where the soil and base are relatively soft. Concrete elements cab be easily lifted if the subsoil settles and placed again on remedied or improved subsoil. Pavements made of precast concrete blocks are used on industrial roads, heliports, airports, town streets, yards etc. (Fig. 4.) [6].

Figure 4 Concrete pavement made of precast elements

2.5 Advantages of concrete pavements

Concrete pavement structures are mostly used on motorways with dense traffic and heavy traffic loads, airport surfaces, industrial floors etc.
Under load, concrete pavements act as a rigid slab supported by an elastic base. Rigid (concrete) pavement, due to its rigidity and concrete strength, distributes the load over a relatively wide surface to the base, therefore the load to the subgrade is very small. However, with flexible (asphalt) pavements, the load is distributed to a smaller surface area, which requires execution of the base in several, thicker courses.

One advantage of concrete over other types of materials is its durability and long service life of concrete structures and concrete pavement structures as well. Service life of concrete pavement structures is 40 years and more. Practice shows that the durability of concrete pavement structures very often exceeds the expected service life, the same being with the expected level of traffic loads which the pavements can bear. These traffic loads are often greater in reality than the designed levels. Remediation of asphalt pavement structures is planned after five years, while this period in concrete pavement structures is significantly longer, spreading to 12 years.
The next advantage of concrete pavement is its safety, because concrete pavements do not leave ruts even after great traffic loads. Increased safety level during travel on concrete pavements is expressed through better visibility, which is a result of the light color of concrete thus giving better vehicle light reflection than on asphalt pavements, all this increasing the safety level during night travel [7].
Cost effectiveness as an advantage of concrete pavements is maintained during construction and is expressed through the following:

- For the same traffic load, concrete pavements are thinner than the asphalt pavements,
- With soils of low bearing capacity, the asphalt pavement has to be 1,5 times thicker than the concrete pavement,
- A smaller amount of aggregates is required for concrete pavements,
- Cements with mineral additives are used,
- Concrete, as material, requires less energy for preparation than asphalt.

Environmental soundness is evident in the fact that secondary (waste) materials can be used in cement and concrete enhancing rational consumption of natural resources [7].

3 Mineral admixtures

3.1 About mineral admixtures

Mineral admixtures are materials which are added in order to improve special properties of cement mortar and concrete. Mineral admixtures are added to cement mortar and concrete by mixing with cement or by adding them to concrete during batching. Mineral admixtures can be divided on natural (pozzolans, diatomaceous earths, volcanic ash) and industrial (fly ash, high furnace slag, silica fume, rice husk ash etc.)
Mineral admixtures are mostly pozzolans. These admixtures are available in larger quantities and much lower prices than chemical admixtures. In the past, natural pozzolans like volcanic soils, tufa, clay and schist in crude or oxidized form were successfully used in construction of various structures like aqueducts, reservoirs and water storage structures. Natural pozzolans are still used in the world. Lately, many industrial byproducts like fly ash, slag, silica fume and terra rosa quickly become the main source of mineral admixtures to cement and concrete. Large quantities of these byproducts are produced each year, suitable to be used as mineral admixtures to cement and concrete.
Mineral admixtures are mainly used as partial replacement for cement which is considered an expensive material. Use of mineral admixtures therefore leads toward significant savings in money and energy as well as toward significant preservation of natural resources. Large quantities of industrial byproducts are used as aggregate for concrete and as fill material in road construction. [3].

3.2 Silica fume

The strength of concrete, as in most materials, is closely connected with porosity. The durability, i.e. resistance of concrete to frost and chemical aggressiveness is primarily based on its impermeability which is logically connected to the quantity of capillary pores. The porosity of hardened cement paste depends on the ratio between water quantity and cement (w/c) during batching of cement composites and on the degree of hydration, i.e. on the time elapsed from their batching [3]. During batching the aim is to create concrete with the lowest possible w/c ratio, in order to improve its properties. However, the w/c ratio can not be decreased without interfering with the workability, i.e. placeability of fresh concrete. In order to obtain fresh concrete with working consistencies and decreased water content, chemical admixtures are used for a number of years already – plasticizers and superplasticizers or high water reducing admixtures.

Along with the already mentioned chemical admixtures an important role in the improvement of the structure and properties of concrete recently has the mineral admixture to cement or concrete, called silica fume. This dust with a high SiO_2 content (85 – 95 %) is waste material from silicon and ferrosilicon production, collected by dusting of smoke gases from electric arc furnaces. Due to the conditions of its generation, silica fume is amorphous and mostly consists of particles smaller than 1m (Fig. 5.) [5].

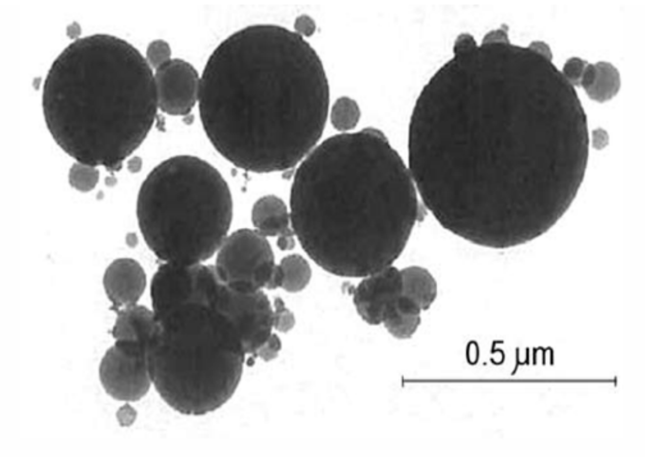

Figure 5 Microscopic image of silica fume particles

Silica fume particles are on the average 100 times smaller than cement particles. During regular proportioning of silica fume, app. on approximately 10% of cement mass, 50000 – 100000 silica fume particles are added per cement grain.

Silica fume in concrete acts as highly effective pozzolan, meaning that it chemically reacts with calcium hydroxide created during hydration of Portland cement. Silica fume in loose state is dark grey to black and the shape in which it is delivered depends on the usage and means of handling [9].

Addition of silica fume results in the decrease of porosity, i.e. the increase in strength and durability of cement composites – concrete and mortars. Except this, the dust contributes to the development of strength and simultaneous decrease of the heat of hydration of cement; it is industrially used in production of cement of low heat of hydration.

Because of its very small particle size, silica fume acts as fluid and its volume mass in original state is approximately 250 kg/m^3. Because of this, silica fume is hard to transport and use. It can be directly added to cement composites (concrete and mortar), or it can be incorporated into cement. In order to be able to add it to cement composites, the silica fume suspension has been prepared in water. This way all the dusting has been avoided and the volume mass of material has been significantly increased, all of which enabled cheaper transport and simpler handling, e.g. proportioning of silica fume (Fig. 6.).

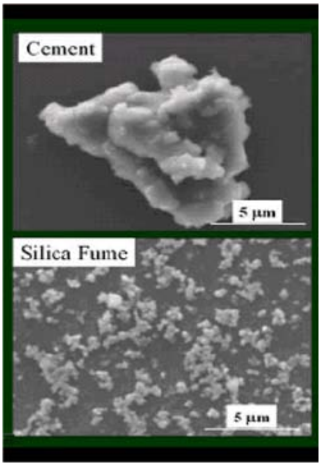

Figure 6 Parallel image of particle size of cement and silica fume

In order that the suspension contains as less water as possible, chemical admixtures are used which at the same time, during concrete preparation, decrease the need for water. When silica fume is present, its large specific surface area causes that the cement composites require more water which in turn causes the already described unwanted increase of their w/c ration [5].

Microstructure of concrete which contains silica fume improves the mechanical properties of concrete as its resistance to chemical reactions. The advantages of concrete prepared with silica fume are as follows:

- Lower permeability and improved durability
- Improved resistance to wear as compared to regular concrete of the same strength
- Compressive strengths greater than 60 N/mm^2 (Fig. 7.) are easily achieved
- Greater bending strength and the modulus of elasticity as compared to regular concrete of the same strength
- Concrete containing silica fume and micro fibers has better resistance properties to exfoliation during fire
- Use of silica fume during preparation of concrete contributes to environmental protection
- Decrease of concrete bleeding
- Speeds up construction (light load traffic can operate after 24 hours)

Silica fume can be used in two ways, as already mentioned:

- As admixture (mostly 8-15% of the cement mass) in order to improve the properties of fresh and/or hardened concrete
- As partial replacement for cement (5-10% cement mass) [9]

3.3 Use of silica fume as mineral admixture to cement

Agglomeration of the original, very fine dust with water into pellets size 1 – 2cm has been established, for easier addition to cement. This increases the volume mass to approximately 650kg/m^3, which is very significant with respect to transport costs. The dusting during handling is also avoided this way, and easier proportioning is enabled. When cement is crushed pellets are ground as well although the distribution of particle size achieved during this process is not equal to the original silica fume particle size. Effect of the silica fume during this form of application is somewhat smaller than during use of original silica fume with large specific surface area. However, this form enables larger quantities of silica fume to be used, solves the problem of transport to the batching plants and its proportioning into concrete [5].

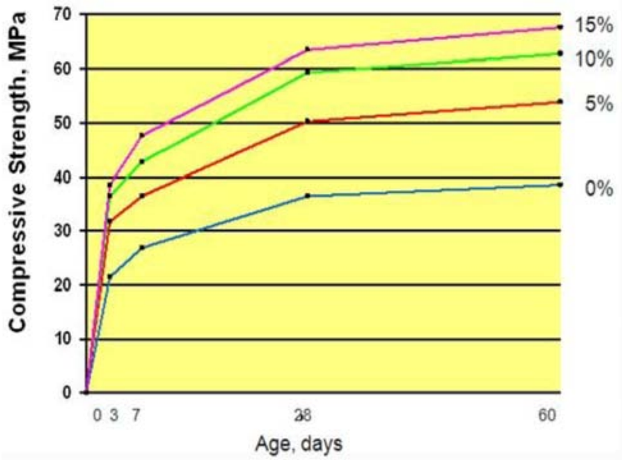

Figure 7 Compressive strength of concrete with different percentages of silica fume

Silica fume is more reactive than other replacement materials such as fly ash. The amount of silica fume added to concrete to improve the compressive strength and resistance to chemicals is usually 5 – 15 % of the cement mass. Steel or polymer fibers can also be added to concrete in order to decrease shrinkage and to improve resistance to wearing.

The proportioning of silica fume to fresh concrete depends on the whether the silica fume is added in the form of powder or emulsion. When using silica fume in the form of powder, it is extremely important to coordinate the batching time, which must be in accordance with the instruction of the manufacturer or the accepted standards. Incorrect batching time can result in appearance of clods, inadequate dispersion and problems during transport. A better way of proportioning is in the form of emulsion, when the emulsion is added in the batching plant during addition of water. The batching time depends on the required concrete consistency or required slump of concrete.

Concrete produced with silica fume even with small amounts (2 – 5% of the cement mass), has an improved finishing and placeability, while bleeding and segregation are decreased in relation to plain concrete. The setting time is similar to plain concrete. Concrete produced with silica fume is susceptible to temperature changes during setting, therefore the strength of concrete increases slowly at low temperatures and faster at higher temperatures. Shrinkage due to drying in concrete made with silica fume admixture is similar as in plain concrete.

Concrete made with silica fume admixture also respects the usual relations between compressive strength and the water-cement factor. The relations between the tensile strength, bending strength and compressive strength are also equal to the relations of these strengths as in plain concrete. The adhesion of steel reinforcement and micro fibers is improved in relation to plain concrete. High levels of compressive strength (more than $25 N/mm^2$ in 24h) can be achieved by adding silica fume, as well as higher tensile strength and modulus of elasticity at equal compressive strengths, than in plain concrete. Concrete with silica fume has excellent resistance to wearing, this being one of the more important criteria for the concrete of concrete pavements.

As in all types of concrete, the correct choice of the composition of concrete mixture, quality control and concrete curing are extremely important factors ensuring all above mentioned advantages of concrete [9].

4 Conclusion

Mineral admixtures are available in larger quantities at a lower price than chemical admixtures. Having in mind that cement is a rather expensive material, industrial byproducts like fly ash, slag and silica fume have become principal sources of mineral admixtures to cement and concrete, which ultimately results in significant savings and preservation of natural resources. Due to its ball-like shape and small particle size, industrial byproducts try to fill in the empty space between relatively large cement grains, which is usually filled with water. As a result, the amount of voids and water requirements are decreased. The volume of voids is also decreased, which results in the change of properties of fresh and hardened concrete.
Mineral admixtures can influence the ratio of concrete mixture, water quantity as well as the rheological properties like workability, bleeding, segregation, setting time, heat of hydration, speed of increase in strength, as well as mechanical properties like tensile strength, compressive strength and bending strength, modulus of elasticity shrinking and creep, durability, resistance to frost, resistance to deicing salt, corrosion of placed steel, resistance to abrasion/erosion. Mineral admixtures also influence the physical properties of cement paste as well as the microstructure of paste after hardening.
The improvement in the area of compressive strength, bending strength, modulus of elasticity and durability of concrete, owing to cement production with admixtures, mark a further stage of development In the past fifteen years, the EU marks a significant increase in production of mixed Portland cement, with mineral admixtures.

References

[1] Beslać, J.: Concrete pavement, Roads and Bridges Magazine, Vol. 12, Zagreb, Croatia, 1973

[2] Jeuffroy, G.: Structural design and construction of pavement structures, Construction book, Belgrade, Serbia, 1975

[3] Krstulović, P.: Concrete properties and technology, University in Split, Croatia, 2000

[4] Skazlić, M. & Bjegović, D.: Development directions of concrete technology, Multidisciplinary conference "Materials and Technology Development", Zagreb, Croatia, May 15, 2002

[5] Popović, K.: Improvement of cement and concrete properties by the use of silica fume, 1st International CANMET/ACI Conference on the Use of Fly Ash, Silica Fume, Slag and other Mineral By-products in Concrete, Montebello, Canada, 1983

[6] Bjegović, D., Beslać, J. & Banjad Pečur, I.: Concrete pavements in the world and in Croatia, 4th Croatian road congress, Cavtat-Dubrovnik, Croatia, October 28-31, 2007

[7] Bjegović, D.: Rosković, R. & Đuroković, M.: Concrete pavements and sustainable development, 4th Croatian road congress, Cavtat-Dubrovnik, Croatia, October 28-31, 2007

[8] www.pavement.com/Concrete_Pavement/Tehnical/FATQ/Materials/Admixtures.asp

[9] Dunster A, Silica Fume in Concrete, Information Paper IP 5/09, www.concrete.elkem.com