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WASTE MATERIALS USED IN MAKING MORTAR AND CONCRETE

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ABSTRACT

Mortar and concrete have been used for thousands of years. However, only in the present century people became aware of contamination of the environment involved in the manufacture and application of these materials. There are ways of using waste created in these processes—and they deserve to be taught. Three distinct advantages are involved in the waste use. First, the material which otherwise would become waste will not contaminate the environment. Second, that material is cheaper than the virgin materials, hence costs are lower. Third, while often the use of a cheaper material affects negatively the properties, this is not necessarily the case here. This is the first review article in a series.

Keywords: *waste mortar; waste concrete; waste recycling*.

1. INTRODUCTION

The demand for construction projects is constantly growing, and thus the production of building materials also increases. Concrete is the most widely used construction material in the world today. Annual concrete production in the world reaches 12 billion tons, which is about 1.7 million tons of concrete per person [1]. Approximately 3.6 billion tons of cement were produced globally in 2011 and cement production is forecasted to increase to 5.8 billion tons in 2050 [2, 3]. However, building material industry, especially cement and concrete industry, induces significant impact on the environment. The production of cement and concrete consumes very large amounts of fossil fuels and raw materials as well as very much energy.

Aware of this situation, practitioners in this field are now developing new materials—significantly different from those used throughout the history. However, because mortar and concrete have been used for so long, there is a certain complacency in teaching about this class of materials in an ‘established’ way. Current modifications in compositions—and the resulting changes in properties—need to be reflected in instruction at the college level. To what extent the students pay attention to changes in this field needs to be evaluated at the same time. It is for these reasons that the present article is only the first one in a series.

Due to the technological process of clinker production and high coal consumption, cement industry emits significant amounts of carbon dioxide into the atmosphere. The production of each ton of cement clinker causes the emission of one ton of carbon dioxide into the atmosphere [4, 5], which accounts for about 7% of global carbon dioxide emission [6, 7]. Limiting carbon dioxide emission by 1 billion tons a year would require replacing about 50% of cement clinker with another low-carbon emission alternative, which would mean the use of about 1.58 billion tons of mineral supplements a year during cement production [6]. Demand for raw materials in building material production is constantly growing and their extraction sources are nearly exhausted. Therefore, one searches for other alternative materials that can be used as raw material partial or complete substitutes.

Excessive exploitation and limited availability of raw materials on one hand, and the problem with the increasing number of industrial waste as well as the lack of landfills on the other hand, have led to the development of studies related to their potential use in building material production. Such method of managing waste is consistent with the principle of sustainable development that assumes efficient management of non-renewable (consumable) natural resources and their replacement with recycled waste substitutes. Utilization of waste materials in construction sector contributes to environmental protection by reducing energy consumption, efficient management of natural resources, and reducing greenhouse gas emissions, especially carbon dioxide, to the atmosphere. Cements with mineral additives are commonly used today in cement industry. Searching for ways to reduce energy consumption and CO_2 emissions will only reinforce this tendency [8]. Fly ash, granulated blast furnace slag or silica fume are used as a partial substitute for Portland cement clinker in cement, or partial substitute of cement in concrete [2, 9-16]. Mortars and cement concretes with mineral additives offer superior features compared to composites made of Portland cement without additives. Mineral additives have effect on the improvement of the rheological properties of concrete mix, mechanical parameters as well as they contribute to the durability increase of cementitious composites[10-13, 17-21].

The use of mineral additives in cement production is growing year by year. The share of cement clinker decreased from 85% in 2003 to 77% in 2010 and is forecasted to decrease even more to 71% in the future [2]. Clinker content in cements produced in Poland is less than 60% [8]. The use of industrial waste causes cost reduction in construction sector, which is also an important aspect. Energy consumption during the production of cements with additives is much lower than in case of Portland cement CEM I production. For example, cement production with 50% of slag additives consumes about half of the electricity and heat[8].

However, cement clinker substitutes are not the only ones that are sought after. The materials that can be used as raw material substitutes during the production of building materials, in particular, mortars and concretes are also interesting. Natural sand is commonly used as fine aggregate in concrete production. Currently many countries suffer from a significant shortage of natural sand of sufficient quality that can be used in concrete production [22-26]. In some countries, specific restrictions have been imposed on the extraction of river sand due to negative impact on the environment [24, 27-29]. That is the reason for searching for different materials that can partially replace sand. Granulated blast furnace slag, fly ash or silica fume, commonly used as mineral additives in cement, can also be used in concrete as a partial sand substitute. Possibilities of using other waste materials, such as natural mineral dust (rock dust) are explored. Additives of marble dust [9, 30-32], quartz dust [33, 34], basalt powder [17, 26, 35-41], granite powder [22, 33] or limestone powder [16, 26, 30, 31, 34, 42-45] have positive influence on the rheological properties of mortars and concrete mixes, cement and concrete strength as well as their durability.

Rock dust is waste that is generated during the extraction and mechanical processing or dedusting mineral aggregates used in the production of concrete and other building materials. These types of waste pose an environmental hazard due to excessive dusting and storage problems. The chemical and mineral composition of dusts is the same as of the bedrock they originate from. This makes them suitable for the production of cement mortars and concretes as a partial substitute of fine aggregate or even cement. Rock dusts, often referred to as stone powders, are used in concrete and cement mortar primarily as inert additives i.e. fillers. Their positive effect on some properties of cement mortar and concrete is mainly related to the filler effect, which results in densifying the cement matrix structure and thus improving mechanical parameters and durability of concrete and mortars. However, not all dusts from processing of mineral aggregates are fully inert. Limestone dust is involved in cement hydration and has some binding properties [43, 46]. Also basalt dust is not completely neutral to cement clinker phases. Some research results show some pozzolanic activity of basalt dust[17, 26, 36, 47, 48]. The paper presents literature overview related to the impact of waste limestone, marble, granite and basalt rock dusts on the rheological properties of concrete mix and parameters of hardened mortar and concrete. The influence of dusts on cement hydration has also been presented. The use of rock dusts as a mortar and concrete component of full value will not only reduce the cost of construction production but also make the management of this waste more efficient. Mortar and concrete with rock dust additives achieve the same and even better physical and mechanical properties as well as durability.

Needless to say, cement and related materials are an essential constituent of instruction in Materials Science and Engineering, Mechanical Engineering, Construction Engineering and more. However, coverage of the waste applications of these materials in teaching is quite limited. The present article should help in correcting this situation.

2. THE CHARACTERISTICS OF WASTE ROCK DUSTS

Let us begin again with noting the amounts of the materials involved. Aggregate production and consumption is over 4 billion tons a year in Europe, most of which, i.e. 91%, comes from natural deposits [49]. Globally, aggregate production is estimated at around 20 billion tons [50]. Although deposits of natural aggregates lie on the earth surface or at low depths and belong to common deposits, the shortage of aggregate, especially natural sand, is presently observed in many countries. This is due to the constantly increasing demand for aggregates used in the construction industry on one hand, and near depletion of natural sources of these raw materials on the other hand. In some countries, strict restrictions have been imposed on the extraction of river sand due to negative impact on the environment and the need to protect valuable natural sites [24, 27-29]. In such situation, one is looking for other materials that can be used as a substitute for natural aggregates in concrete production.

As a partial substitute for fine aggregate, i.e. sand, the following can be used: blast furnace slag [51-54], fly ash [55-57], silica fume [58, 59] as well as stone dust. They constitute waste that is created, among other things, in the production process of crushed-stone aggregates. During rock extraction and mechanical processing, and due to their sorting, large quantities of waste material are produced in the form of stone dust. Storage and disposal of this type of fine material poses serious environmental problems. Dust released to the atmosphere significantly contributes to the accumulation and harmful dispersion of fine solids in air, water and soil[60, 61]. The pollution of air with solid particles poses a health hazard. Particles inhaled by human beings and animals may cause respiratory distress and may contribute to asthma and allergy [23, 62]. Similarly, dust waste is produced at the dimensional stone industry, where mainly marble and granite used for the production of floors, paving, cladding, gravestones, statues and monuments is processed. Globally, the dimensional stone industry processes about 68 million tons of rock each year[30]. Countries where more than one million tons of stone per year is processed are China, Italy, India, Portugal, Brazil, Turkey, the USA, Greece, France and South Africa [30]. The technological process of cutting quarried blocks to the right size and then grinding and polishing them involves water that is used to cool and lubricate the sawing and polishing machines. This type of stone machining results in producing about 20–30% of waste in the form of semi-liquid sludge [4, 63-68]. The sludge is stored in special settling tanks and then — in the form of pulp, transferred to a landfill [23]. Part of water from the pulp penetrates the ground, thus paving the way for fine dust particles that block pores in the ground. This greatly contributes to the reduction of soil permeability, which has a negative impact on groundwater level and soil fertility[23, 60, 69]. Part of water evaporates and dust, after drying, is emitted into the atmosphere, posing a threat to people and the environment [30, 70]. Dusts in crushed aggregates are formed as a result of crushing bedrock. In contrast, in case of natural non-crushed aggregates there may be dusts clay as well generated by natural weathering processes. Particles of clay as well as natural mineral dusts may form layers on the surface of the aggregate grains; this reduces the adhesion of the cement paste to aggregate grains resulting in lower concrete strength. Moreover, clay particles can be absorbed on the surface of cement grains, thus interfering with hydration reactions [27, 30]. The addition of clay that easily expands with water also adversely affects the quality of mortar and concrete. For this reason, these materials should not be present in the aggregate.

Students deserve to be taught about the national and international regulations and their effects on the behavior of industry. Country-specific standards contain requirements that define dust content limits in aggregates used for concrete production. The European standard EN 12620 lists categories of maximum dust content that should be declared by aggregate manufacturers. Total dust content less than 3% of aggregate mass in fine aggregate has been considered to be harmless. According to the British regulation BS-EN 12620, the maximum content of grains smaller than 75 μm cannot exceed 4% in case of coarse aggregate and, depending on concrete application, 10-14% in fine aggregate. American guidelines set out in ASTM 33 limit the maximum dust content to 3% in aggregates used for the production of abrasion exposed concrete and 5% in case of other concrete types. If permitted dust content is exceeded, the aggregate must be washed before use in concrete. Fine material obtained this way is dusty waste. Some authors rightly point out that dust classification as a harmful material in concrete only by grain diameter is not appropriate [27, 30]. It is true that natural mineral dust that adheres to the surface of aggregate grains is not desirable in concrete, as described above. However, while added to the concrete mix or mortar, it constitutes a component of full value, which has positive influence on the technological properties of the mixes and the properties of hardened composites.

At first, the aggregate was considered to be chemically inert. In fact, however, the aggregate is not completely inert, and its chemical properties affect the parameters of concrete [71]. Kurdowski [8] claims that relatively little attention is paid to the chemical and mineral composition of aggregates during concrete design. Garbacik *et al*.[72] proved that albite, the mineral from feldspar group, reacts with calcium hydroxide in solution in the matrix pores. Calcium ions from calcium hydroxide $Ca(OH)_2$ diffuse into the surface layer of albite and substitute sodium ions in its structure. This leads to the surface transformation of albite layer into C-S-H phase, which has positive influence on the structure of the interfacial transition zone (ITZ) [72]. Calcium carbonate $CaCO_3$, the main component of limestone dust, however, is reactive with cement aluminum phases, and its reactivity increases with the degree of dust fragmentation[46]. The addition of calcium carbonate also affects the hydration acceleration of tricalcium silicate C_3S. Some studies show some activity of basalt dust[17, 26, 36, 47, 48]. The negative impact of aggregate on concrete properties is also worth mentioning. As an example, it may be the reaction of aggregates containing reactive silica (opal, tridymite, silica glass) with sodium and potassium hydroxide in cement, which causes concrete expansion and cracking [8, 73]. Unfavorable concrete expansion is also caused by rock-forming minerals containing magnesium ions, such as pyroxenes and olivines[8]. Considering high dust fineness and significant dust dispersion in the cement matrix, it seems very important to recognize the dust particles reactivity of different rock material origin against the components of cement paste.

The mineral and chemical composition of natural mineral dust is determined by the composition of bedrock the dust originates from. Limestone is the most widespread carbonate sedimentary rock composed of calcium carbonate. Contemporary limestone deposits consist of calcite and aragonite $CaCO_3$, whereas metastable aragonite in older formations was transformed into a permanent modification of calcium carbonate – calcite[74, 75]. Chemical composition of limestone is dominated by calcium oxide CaO. Marble is a metamorphic rock formed by the transformation of carbonate rocks. They are nearly monomineral rocks made of calcite and dolomite with minor additives such as diopside or mica [75]. Chemical composition of marble is dominated by calcium oxides based on CaO and magnesium oxides based on MgO.

Granite is a plutonic igneous rock, the mineral composition of which is dominated by alkaline feldspars (orthoclase, microcline, perthite, albite), quartz and plagioclases [76]. The chemical composition of granites is primarily silica SiO_2 and aluminum oxide Al_2O_3. By contrast, basalt is an extrusive igneous rock. The composition of basalt is dominated by minerals from the feldspar group, i.e. the so-called plagioclases accompanied by pyroxenes and amphiboles. Chemical composition is dominated by silicon oxide SiO_2, aluminum oxide Al_2O_3 and iron oxide Fe_2O_3. Natural rock dust generated during the fragmentation of solid rocks has irregular sharp-edged shapes and a rough surface. Examples of scanning electron microscopy (SEM) images of rock dust generated from limestone, marble and basalt rocks are shown in Figure 1.

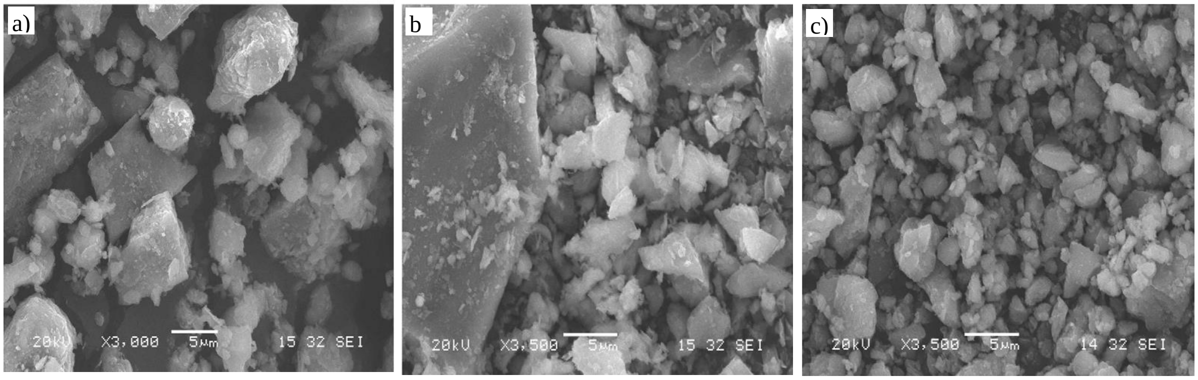

Figure 1. SEM macroscopic images [77] of: a) limestone dust, b) marble dust, c) basalt dust

3. CEMENT HYDRATION WITH STONE DUST ADDITION

Students usually know from everyday life that water is poured multiple times on a slab for a new house. The activity of mineral additives in relation to cement clinker phases depends primarily on their chemical and mineral composition, fineness and especially on the content of reactive phases such as glass or zeolites. The activity of those additives is also strongly influenced by the chemical composition of a pores solution in the paste [78]. It is therefore quite important to know how specific mineral additives affect the hydration process of cement clinker phases. Some mineral additives affect the cement hydration, and specifically the reaction rate with water, i.e. the thermal effects of the hydration process, the phase composition of the cement paste, mainly the $Ca(OH)_2$ content, thus also the chemically bound water. Such changes in a process of cement hydration with mineral additives may result from chemical or physical interactions. Chemical reaction of additives is primarily related to their pozzolanic properties. Pozzolanically-active mineral additives are dissolved in the high alkalinity pores solution in cement paste, releasing siliceous ions into the liquid phase $[H_3SiO_4]^-$ [8, 79]. These ions react in solution with calcium ions to produce a C-S-H phase, both in the paste pores and on the surface of the mineral additive particles. Available research results indicate some pozzolanic activity of some stone dust [17, 26, 36, 47, 48].

However, in most cases, the impact of rock dust on cement hydration is mainly related to their physical interaction. Physical interaction of inert mineral additives with cement hydration involves two overlapping phenomena, namely the increase of the effective w/c ratio and the filling of the pores by hard and high-strength particles of mineral dust. The first factor plays a role in the case of the partial replacement of cement with a mineral additive. Since additives are slower to react with water, an increase in the effective w/c ratio is observed, and the rate of cement-water reaction increases. Of course, less cement content means fewer hydration products in the paste—if we assume its complete conversion. The content of hydrates with some stone dust in the early hydration is higher than in the case of cement without additives [80-82]. Some authors[78, 83, 84] explain this fact that, as previously stated, increasing the w/c ratio accelerates the cement hydration.

The influence of inert mineral additives on the hydration of cement clinker phases is related to the role of heteronuclei; this has been demonstrated, for example, in the case of calcite by Ramachandran and Zhang Chun-Mei [46] as well as by Nonat *et al.*[85]. The former [46] have proven that the addition of fine-grained calcite contributes to the shortening of the induction period and the intensification of the second peak on the microcalorimetric alite curves. They conclusively proved the formation of C-S-H phase on the surface of calcite particles—what demonstrates the role of this mineral as heteronuclei. Gutteridge and Dalziel [81] have come to the same conclusions and found that the addition of rutile powder accelerates cement hydration—what results in the hydration degree increase of main clinker phases and the increase in portlandite content. Compared to cement paste without additives, Rahhal and Talero [82] found a lower content of calcium hydroxide in paste, both with limestone and quartz additives. The content of calcium hydroxide decreased with dust increase, which in this case is not related to the pozzolanic reaction but mainly to the change in phase composition of the paste as a result of partial replacement of cement with dust. The beneficial effect of stone dust on the hydration process has also been confirmed in the cement hydration heat test [80, 83, 84, 86-88]. The efficiency of this process largely depends on the surface area of the specific dust and its contribution to the cement paste [80, 83, 84, 86]. Berodier [80] found the relation of the hydration rate increase to the amount of additive and its fineness—seen in the results of calorimetric studies of the heat evolution rate during cement hydration. At the same quartz fineness, the hydration rate increases with increasing the replacement content of cement with quartz, i.e. with the increase of total specific surface area of the

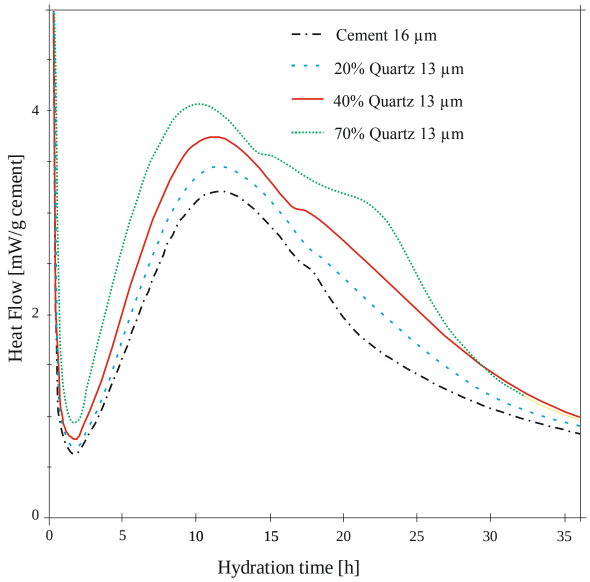

Figure 2. The relationship between the hydration heat evolution rate and the replacement of quartz in cement paste [80].

filler (Figure 2). The increase in total specific surface area also increases the surface area available for crystallization of hydration products of cement clinker phases.

The beneficial effect of marble dust on the cement hydration process has been demonstrated by Jain [89]. The cement hydration degree increased with the increase of dust replacement with grains smaller than the cement grains and decreased when dust with larger grains than cement grains has been used. Bonavetti and Irassar [33] showed, however, that the addition of granite dust slows down slightly the hydration rate, regardless of its content in cement. This is not consistent with the previous results of studies on the effect of quartz dust on hydration [80, 83, 84, 86], since it is known that granite contains from 40% to 50% of quartz [90]., This discrepancy, however, might be related to very large differences in fineness of this mineral additive.

The acceleration of hydration associated with the role of mineral fillers is particularly evident in the early period of cement hydration. The efficiency of this process does not depend on whether the additive is chemically reactive to cement clinker phases or chemically inert [78]. During this period, the acceleration of cement hydration is observed mainly as a result of physical interaction of the fine-grained mineral additive [78, 80, 81, 83, 84, 86, 91]. The chemical reactivity of active mineral additives, such as blast furnace slag, fly ash or silica fume, is small in the early hydration period, and their effect on the hydration process in this period is mainly related to the filler effect [78, 80, 83, 84]. The chemical reactivity of mineral additives usually appears after the main peak on the micro calorimetric curves, i.e. during the slowdown of the hydration process [80]. Berodier and Scrivener[86] found that both slag and chemically inert quartz affect the early stages of cement hydration process in a similar way. Similarly, the course of micro calorimetric curves (Figure 3) indicates that the chemical reactivity of slag is not revealed during the early period of hydration process. Heat evolution rate during cement hydration with slag additive is higher than that of fine-grained quartz only after about 28 hours. This proves the beginning of the chemical reaction of slag with cement clinker components[80, 84]. The same conclusions have been drawn by Laibao *et al.* [17] in the case of basalt dust and fly ash additives.

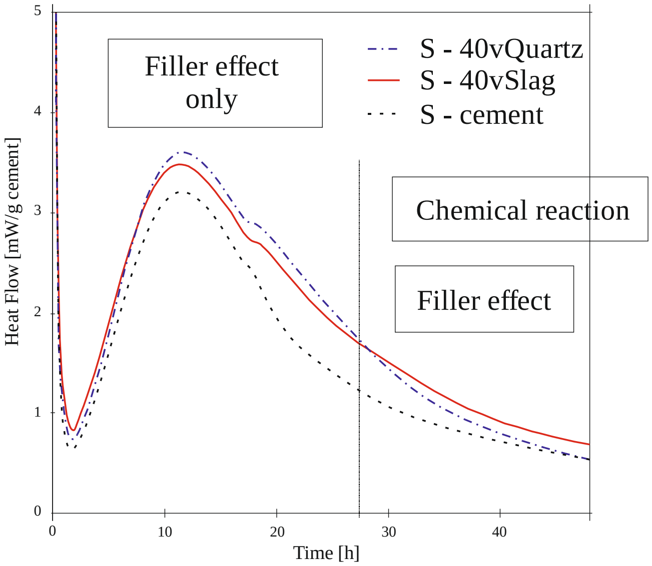

Figure 3. Heat evolution rate of cement hydration without additives and cement with 40% addition of quartz dust and slag[84, 86]

As mentioned above, the acceleration of cement hydration with crystalline mineral additives is increased when replacement of cement content with these additives increases. However, Berodier and Scrivener [86] note that after some time the physical effects of additives no longer have a significant influence on the hydration process (i.e. filler effect), this regardless of the grain size, and therefore unrelated to the specific surface area of the crystalline additives. The chemical activity of the mineral additive begins to play a major role at a later hydration period.

Many researchers have found that the addition of crystalline dusts of various mineral composition contributes to the increase of non-evaporable water by hydrated cement, and thus denotes their chemical activity [26, 33-35, 81, 82, 87]. Soroka and Setter [26], as well as De Weerdet *et al*. [87] found that the content of chemically bound water in hydrates, and thus the degree of cement hydration, increases along with the increase of limestone dust content and its fineness. This view has been shared by Rahhal *et al*.[34, 82] who studied the effect of limestone and quartz dust on cement hydration. Similar conclusions have been drawn by Knop *et al.* [92] who studied the effect of limestone dust on the hydration rate based on cement setting time. It should be noted, however, that in case of limestone [calcite] the content of hydration products varies considerably, since hydrated calcium aluminate carbonates are produced and they contain more water in their structure[8]. Stark *et al.*[88] noted that the addition of finely ground calcite reduces the induction period due to faster nucleation of C-S-H phase on its grain surface. The introduction of fine-grained calcite contributes to the increase of the area where active centers are favorable for the nucleation of the C-S-H phase. The chemical affinity of the C-S-H phase in relation to calcite also plays very important role[88]. Also, Berodier [80] has found that, in comparison to quartz, the addition of fine-grained limestone is much more effective in reducing the induction period and increasing the cement hydration rate. In case of cement with limestone and quartz additives, she found that the surface of limestone grains was completely covered with the nuclei of C-S-H phase at the end of the induction period, which was not observed on the surface of quartz grains. At the same time, only a small amount of dispersed C-S-H nuclei was present on cement grains. After 5 hours, limestone grains were densely covered with needle-shaped forms of C-S-H phase oriented perpendicularly to the grain surface, while no significant difference was observed in case of cement grains, compared to the earlier image. Bonavetti *et al.* [93] claimed, however, that the addition of fine-grained limestone accelerates the formation of ettringite and delays the ettryngite conversion into monosulfate.

The influence of basalt dust on cement hydration rate is not only related to the physical but also to the chemical effect of this additive. A large area of basalt dust can facilitate the crystallization of cement hydration products, which undoubtedly contributes to increased hydration degree. Many researchers also found that the pozzolanic activity of basalt dust is not to be underestimated [17, 26, 36, 47, 48]. Saraya [36] notes that the effect of fine-grained basalt additive on cement hydration can be divided into two stages. In the first stage basalt acts as a filler and its effect on early cement hydration is related to physical interaction, which is consistent with the research results of other authors on the effect of various fine-grained crystalline additives on cement hydration[33, 80, 83, 84, 86-88, 93]. The second stage consists of slower mineral reactions in the aggregate with ions in solution in cement paste. Some minerals found in basalt react more easily with the ions in the pores solution in concrete (mortar) to form an amorphous or microcrystalline C-S-H and C-A-S-H phase [36]. The influence of fine-grained basalt on cement hydration was also studied by Kmecova and Stefunkova [35]. Based on thermal tests, they quantitatively assessed the products of cement hydration in cement mortar without additives as well as with the addition of basalt dust as a partial sand substitute. Just as Abdelaziz *et al*.[47], Kmecova and Stefunkova [35] found higher content of C-S-H phase in mortar with basalt dust than in the mortar without additives after 1, 28 and 90 days of mortar hardening. On the other hand, calcium hydroxide showed opposite changes.

The pozzolanic activity of basalt dust has also been confirmed by Laiboa *et al*. [17] and Abdelaziz *et al*. [47] who, based on X-ray studies, found lower content of calcium hydroxide in the grout with basalt dust additive than in the cement grout without additives.

4. TECHNOLOGICAL FEATURES OF MORTARS AND CONCRETE MIXES WITH ROCK DUST ADDITIVES

Workability and consistency are the factors that are essential in determination of concrete mix properties. Water demand and workability of the concrete mix depend to a large extent on the specific surface area of mix components. However, Neville [71] notes that workability is not a simple function of specific surface area; aggregate particles smaller than 150 μm behave in the mix like grease and do not require wetting to such extent as in the case of coarse grains. The influence of specific fine grain surface area on the concrete mix workability is, however, not precisely defined [71]. The increase of fine-grained material in the cement mass modifies the rheological properties of paste and therefore it affects the workability of mortar and concrete mix. Replacing the cement with a finer dust material contributes to increased water demand, that is the amount of water required to achieve standard consistency, which is related to the increase in specific grain surface area. However, the increase in the specific surface area does not always lead to the increase in water demand. The addition of fly ash to concrete mix can reduce water demand at the same workability by 5–15%, which is related to the grain shape of fly ash[71]. The spherical shape and smooth surface of fly ash grains produces the "ball bearing" effect. This phenomenon contributes to the reduction of interpartical friction, and thus improves workability.

Stone dust produced as a result of the processing of natural aggregates has irregular shape and rough texture, which increases the internal friction between dust grains as well as between cement paste and coarse aggregate[61]. Therefore, greater water demand and worse workability of concrete mixes with rockoriginated dust additives should be expected. Yet some authors point out that the addition of rock dust, as a replacement of some cement, in some cases improves rheological properties of mortars and concrete mixes and have positive effect on workability [92, 94-98]. This is the result of physical interaction of stone dust grains; due to the very small grain size, they increase the packing density and reduce the voids volume between particles [99]. High density mix of particle packing causes that less water is trapped between the grains and thus more water is available to wet the grain surface. This contributes to an increased flow and better workability of the mix. The amount of water required to obtain standard consistency i.e. water demand indicates the total volume of free space between grains, thus the density of particles packing [92]. In case of cement blended with stone dust, the dust material is to be understood as cement and stone dust while the dust material density will then be the weighted average density of cement and dust [100].

Knop *et al.* [92] report that the packing density of cement particles and limestone dust as well as water demand, i.e. the amount of water needed to achieve paste standard consistency, depends on the size of the dust particles used as cement substitute. Laibao *et al.* [17] studied the influence of basalt powder on standard paste consistency. Authors point out that irregular sharp-edged shape of basalt grains has great influence on water demand, which increases the specific surface area and their rough and angular surface. Adelaziz *et al.*[47] studied the influence of limestone and basalt dust on standard paste consistency. Just as other authors, they also found that share increase of dust with a smaller grain size than cement particles size increases the amount of water at which paste reaches standard consistency. Aliabdo *et al.*[63] as well as Vardham *et al.*[60] noticed that the amount of water required to achieve standard consistency is only slightly reduced with the share increase of marble dust of comparable surface area to cement.

There are also test results related to the rheological properties of concrete mixtures, where rock dust was introduced as a replacement for a part of fine aggregate (sand). Stone dust has significantly greater specific surface area than sand, therefore it increases water demand and the amount of water required to achieve the desired consistency. With a constant w/c ratio, the mix is less workable compared to the mix without stone dust additives[42]. The mix consistency changes towards less liquid[9, 42] and its workability decreases[61] along with the share increase of rock dust in the sand mass.

The above-mentioned results refer to concrete mixes prepared without admixtures - while such mixes are produced less and less. Uncik and Kmecowa [37] found that the partial replacement of cement with basalt dust does not affect the consistency of mortar without a super-plasticizer. On the other hand, the mortar workability improved with the replacement of cement with basalt dust at the constant content of the superplasticizer. These results are consistent with the results of Ramezanianpour *et al.* [101] who showed that the constant amount of superplasticizer decreases the amount of water required to obtain the required concrete mix consistency. Just as Almeida *et al.*[30], they showed that introduction of small dust amounts as a replacement of sand, i.e. up to 10% of sand, reduces the amount of water required to achieve the intended consistency at a constant plasticizer content. It can be concluded that the negative impact of the specific surface area on rheological properties of the mixture is reduced with the use of admixtures. In a sense, the influence of the irregular shape of rock dust grains on friction between the grains is also minimized, which has a positive effect on concrete mix workability.

5. MECHANICAL AND PHYSICAL PROPERTIES OF MORTAR AND CONCRETE WITH STONE DUST ADDITION

The influence of stone dust on mechanical parameters of cement composites depends mainly on the stone dust replacement and the specific surface area of this additive. Partial replacement of cement for stone dust generally results in deterioration of mortar and concrete strength parameters, which is obviously related to lower cement content (Figures 4 and 5).

However, some authors have observed that a slight dust share in cement mass, i.e. up to about 5–10%, causes the strength to increase compared to material strength without dust additives. Lawrence *et al.*[109] have noted that the strength of the cement mortar increases when the specific surface area of stone dust increases. Knop *et al.*[92] have come to the conclusion that cement mortar with limestone dust additives that features smaller particle size than cement particles achieves better early strength than control mortar, that is without dust additives. In the later period, i.e. after 28 days the situation is reversed and the strength of the control mortar is then higher than the strength of the mortar with dust additives. The authors have reported different results in case of mortar with additives featuring similar and larger grain size than cement grains. In such case the mortar strength with dust additives in early curing was lower than that of the control mortar. Higher value, however, was reached after 28 days. Tsivilis *et al.*[106] came to the same conclusions.

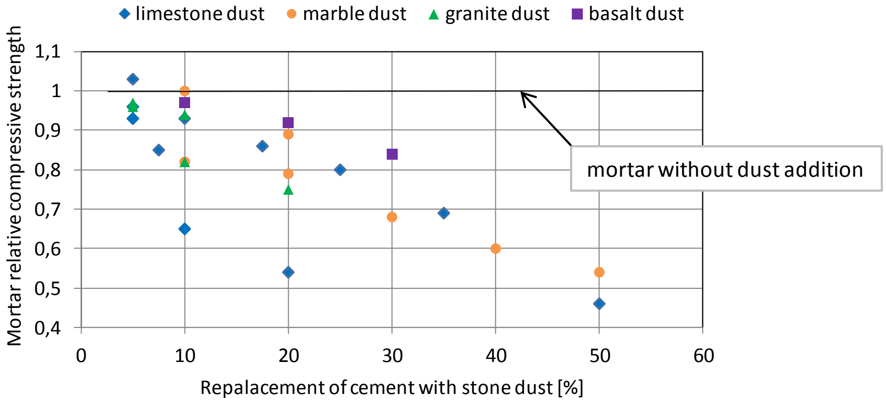

Figure 4. The influence of stone dust on the compressive strength of cement mortars after 28 days of hardening. Dust acts as a partial cement replacement (limestone dust[1, 17, 87, 92], marble dust [60, 63, 102, 103], granite dust [104, 105], basalt dust [37]).

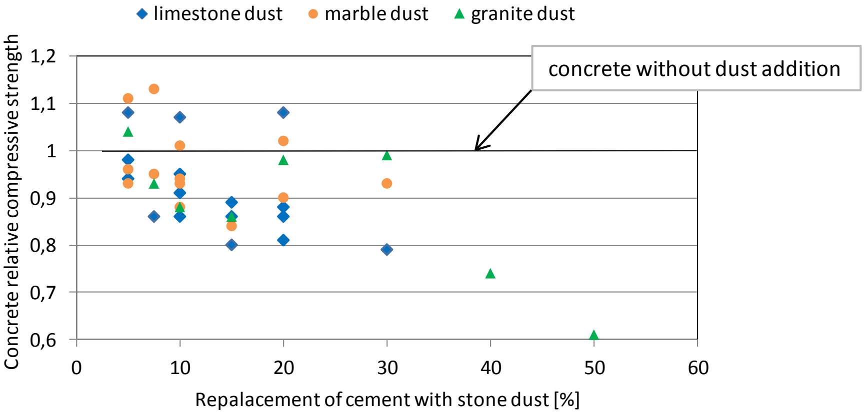

Figure 5. The influence of stone dust on the compressive strength of concrete after 28 days of hardening. Dust acts as a partial cement replacement (limestone dust [1, 6, 68, 77, 101, 106], marble dust [63, 68, 77, 107], granite dust[108]).

Much more favorable results with reference to mechanical parameters of cementitious composites were found in the cases of using stone dust as a substitute of fine aggregate. Most authors believe that the introduction of rock dust as a replacement for the part of sand contributes to the improvement of physical and mechanical properties of mortars and cement concretes (Figure 6 and 7). As early as 1976, Soroka and Stern[110] noted the positive effect of fillers on mechanical properties of cement mortars. Strength increases with the replacement of dust in sand mass and with the increase of its fineness. The same conclusions have been drawn by many authors who have studied mortars and concretes with the following additives as replacement for sand: limestone dust[26, 42, 47, 111, 112], marble dust [9, 63, 66, 67, 103], granite dust [22, 23, 28, 33, 61, 62], and basalt powder [26, 35, 38, 41, 47].

The strength increase in cement composites with stone dust additives is primarily related to the heteronucleation of hydration product of cement clinker phases on dust grains and to the filler role of stone dust. The operation mechanism of inert dust neither depends on the type of rock raw material the dust originates from nor its chemical composition[26, 109]. Grading of stone dust is therefore much

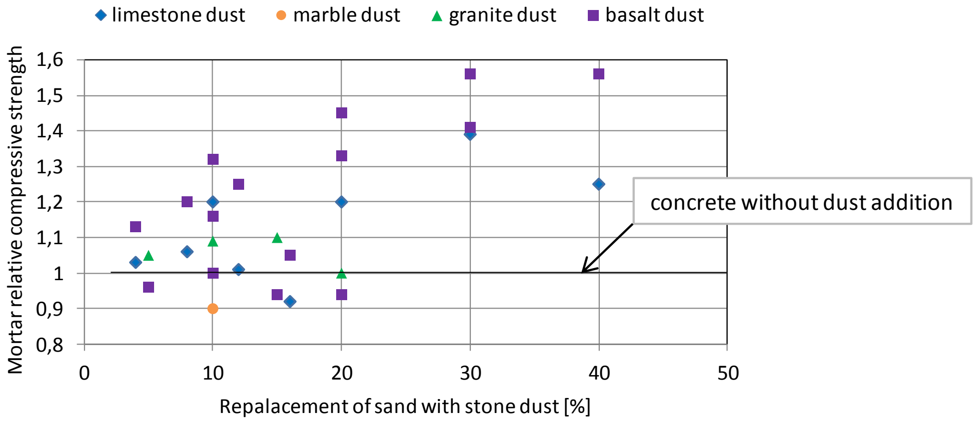

Figure 6. The influence of rock dust on the compressive strength of cement mortars after 28 days of hardening. Dust acts as a partial sand replacement (limestone dust[26, 47], marble dust[103], granite dust[33], basalt dust[26, 35, 40, 47]).

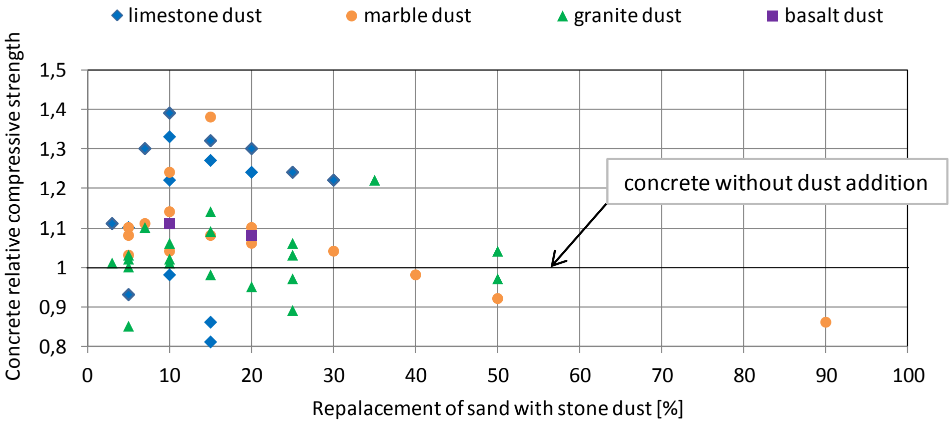

Figure 7. The influence of rock dust on the compressive strength of concrete after 28 days of hardening. Dust acts as a partial sand replacement (limestone dust[42, 66, 111, 112], marble dust[9, 63, 66, 67], granite dust[22, 23, 28, 61, 62], basalt dust[41]).

more important here. However, it should be noted that the specific surface area of dust is much more important in shaping the mechanical parameters of mortars and concrete when dust acts as a partial cement substitute than in case of replacing fine aggregate (sand) with dust. Partial replacement of cement with finer grain size and greater specific surface area than cement leads to increased number of nucleation sites of hydration products. Since hydrates can be crystallized not only on cement particles but also on the surface of stone dust, the rate and hydration degree of cement clinker phases is increased. This results in an additional amount of C-S-H phase, lower porosity of cement matrix, and thus greater paste strength, especially at early hydration period[92]. Replacing cement with dust with larger grain diameter reduces the specific surface area where crystallization of hydration products is possible. It results in lower hydration rate, lower hydration degree and lower early strength at the same time. The introduction of stone dust as sand replacement leads in each case to the increase of the specific surface area of nucleation centers, and in this case, it is independent of whether the dust fineness is smaller or larger than cement.

Heteronucleation on the surface of additive particles plays an important role mainly in the early strength of cement composites [30, 109]. Soroka and Setter [26] claim that the mortar early strength increase results more from accelerated hydration of cement clinker phases as a result of hydration of nucleation products on the surface of cement and additive particles than from the densifying effect of cement matrix. In a later period, however, heteronucleation effect is no longer so important in shaping mechanical parameters and the increased strength of composites with dust additives is primarily related to the filler role of stone dust[70, 92, 109].

Fine dust material acts as an inert filler, which contributes to better filling of the intergranular free space in a composite. This results in a more dense cement matrix structure, lower porosity and therefore greater strength[8, 33]. The special role of particle packing to achieve optimal properties of cements and concretes is discussed at length by Roy *et al*.[113]. Microfiller introduction causes greater dispersion of cement grains, which contributes to the accelerated hydration of cement clinker phases[8, 61].

Abdelaziz *et al*.[47] claim that, in case of mortar with basalt powder, strength increase is related both to filler effect and to basalt pozzolanic activity. As a result of the reaction of basalt dust with calcium hydroxide $Ca(OH)_2$ an additional C-S-H phase is generated, which in turn leads to the increased density of cement matrix and therefore to strength improvement. This is the main reason of higher strength of mortars with basalt dust additives, compared to, for example, mortars with limestone dust[26, 36, 47].

With a certain stone dust share in the mass of fine aggregate, the decrease in strength of mortar and concrete is visible. Fine grain dust features large surface area and therefore more water is needed to wet the grain surface. Too much dust content leads to the reduction of available water needed to hydrate cement clinker phases[35]. Alyamac and Aydin[9] noted that high dust content causes the interruption of grain-size distribution, which results in more free space between grains and consequently – lower strength. Knop *et al*.[92] also note that high content of very fine dust particles causes their agglomeration due to interpartical interactions resulting in massive grain aggregates with a diameter exceeding even 100 μm. This leads to a decrease in effective specific surface area and lower packing density of particles, which directly affects strength reduction.

Alyamac and Aydin[9] and Genzel *et al*.[114] indicate the positive impact of stone dust not only on strength, but also on the abrasion resistance of concrete. Based on the studies of concrete with marble dust additives, they found that abrasion resistance increases with the increase in concrete strength along with the increase of dust share in fine aggregate. The positive effect of stone dust on the abrasion resistance of concrete has been confirmed by Binici *et al*.[66] who used marble and limestone dust as a partial sand substitute (Figure 8).

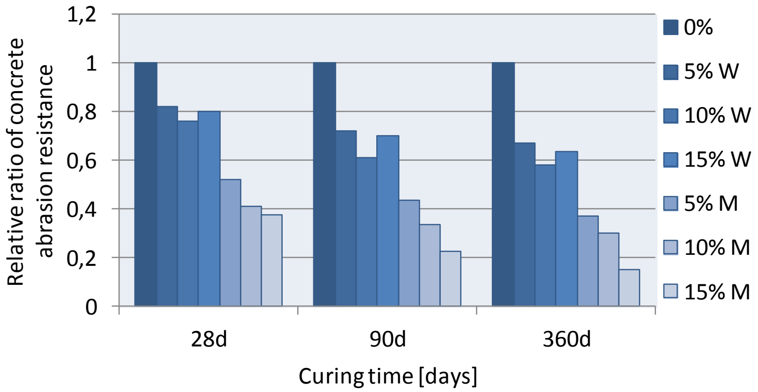

Figure 8. The influence of limestone (W) and marble (M) powder on the abrasion resistance of concrete[66]. Abrasion strength of concrete has been determined by changing the mass of the sandblasted sample relative to the mass of the control sample.

Direct relationship to concrete strength depends on the porosity of cement matrix. The research results of several authors indicate positive influence of stone dust on cement paste porosity[30, 33, 44, 67, 87]. As previously mentioned, due to the heteronucleation on additive particles, the hydration degree of cement clinker phases with dust additives increases, and therefore the volume of hydration products also increases, leading to porosity reduction[33, 87]. Evenly distributed in cement matrix, rock dust particles fill capillary pores and contribute to the reduction of their diameter, resulting in a denser matrix structure and thus its greater strength[44, 92, 115]. Concrete strength is primarily a function of free space volume within concrete. However, total porosity is not sufficient to determine strength, which is also influenced by the structure and shape of the pores as well as the distribution of their dimensions. The greater fine pores content in total porosity, the greater the strength[116]. Uchikawa *et al.*[44] found that the addition of limestone dust does not affect the overall porosity, but changes pore size distribution. Dust additive resulted in a decrease in the volume of pores larger than 100 nm and, at the same time, an increase in the volume of smaller pores, i.e. 6–50 nm in diameter and even gel pores smaller than 6 nm.

There are few studies in literature that include study results of the influence of stone dust on concrete shrinkage. Bonavetti and Irassar[33] as well as Celik and Marar [42] studied the shrinkage of mortars and concretes with dust additives that were used as a partial replacement of sand. The results show that dust additive increases the shrinkage. The same authors [42] note that the concrete shrinkage increases with the increase in concrete strength caused by stone dust additives. In other words, stronger concrete is more stiff but shows more shrinkage at the same time. Aitcin [117] declares that the increase in coarse aggregate content in concrete with simultaneous reduction of fine aggregate causes the reduction in concrete shrinkage. Thus, by analogy, it can be assumed that replacing "coarser" sand with finer dust will adversely affect concrete shrinkage.

6. CONCRETE DURABILITY WITH ROCK DUST ADDITION

One of the most important factors that define concrete durability is permeability, which can be considered as the resistance of concrete to penetration and movement of aggressive substances within concrete, both in the form of liquids and gases[71, 118]. The study results presented in the literature indicate that cement paste with stone dust additives of different mineralogical origin show lower water permeability than paste without such additives[30, 42, 112, 119]. Permeability of water depends primarily on the volume of capillary pores. However, it is not only related to the overall porosity but also to the size, distribution, shape, tortuosity and continuity of pores[8, 71]. Mehta and Manmohan [120] claim that the permeability decreases when the content of fine pores increases and the content of larger capillary pores decreases. It is known that the content of capillary pores increases when the w/c ratio increases. Therefore, permeability factor increases exponentially with the w/c ratio, and decreases with time and the degree of cement hydration[8]. Reducing the permeability of cement paste with stone dust is mainly related to physical dust interaction, i.e. their role as microfillers. Stone dust particles break the continuity of capillary pores and thereby contribute to the reduction of capillary water uptake and permeability[30, 42, 119]. Hetero-nucleation has a substantial effect on lower cement paste permeability with stone dust additives, which promotes the formation of the crystallization nuclei and the densifying of cement paste. As mentioned earlier, stone dust additives have impact on the acceleration of cement hydration, which directly contributes to the reduction of capillary pore content due to the filling of free space between particles with hydration products.

Another factor that affects concrete strength is concrete water absorption. Water absorption is related to the ability to absorb water, that, like permeability, is a function of size, distribution, shape, tortuosity and continuity of pores[106]. Almeida *et al.*[30] as well as Celik and Marar[42] found that 15% of limestone dust in the sand mass reduces concrete absorption due to both the reduction of pore volume and the breakage of their continuity. The positive influence of stone dust on the concrete absorption of water has also been found by Alyamac and Aydin [9] as well as Gameiro *et al.* [121], who used marble dust as partial sand substitute. Study results related to concrete with limestone and marble dust additives used as a replacement for part of cement presented in the publications indicate the increase of water absorption when particles size is greater than cement particles size [1, 6, 65, 101]. Tsivilis *et al.* [106], Gesoglu *et al.* [68] as well as Tasdemir [122] claim that the stone dust additives of larger specific surface area than cement cause porosity reduction - what results in reduced absorption and larger concrete resistance against penetration of aggressive media.

The most aggressive media that cause the corrosion of concrete are chlorides. Chloride ions migrate inside concrete and substitute OH- hydroxide ions in cement hydrates during leaching. OH^- ions, after being transferred to the solution, diffuse into the surface layers of concrete, which leads to lower pH of solution in pores. Concrete resistance against the migration of chloride ions is therefore closely related to the porosity and permeability of concrete. Pore structure, particularly the content of gel and capillary pores, plays a very important role during ions diffusion. The content increase in gel pores and the continuation breakage of capillary pores significantly reduce the effective diffusion coefficient [8]. Stone dust additives contribute to the densifying of cement matrix structure and changes pore size and structure, as previously stated. Heterogenic nucleation on the surface of additive particles leads to the increase in content of the C-S-H phase. This results in a content increase of fine pores and a breakage of capillary pore continuity, and therefore it reduces the rate of ions diffusion. Uysal *et al.*[77] studied the influence of limestone, basalt and marble dust on the concrete permeability in relation to chloride ions. The authors have shown that migration ability depends on the fineness of the cement substitute additive. Limestone dust of particles larger than cement grains increased concrete permeability compared to basalt and marble dust the grains of which were finer than cement grains. Celik *et al.*[6] came to similar conclusions and they found higher resistance against the migration of concrete chloride ions with basalt dust additive of comparable particle size to cement particles. Opposite study results, i.e. higher value of chloride ion diffusion coefficient, have been found in case of partial cement replacement with limestone dust of larger grain size. The influence of limestone dust additive on the reduction of chloride ion diffusion coefficient was found by Heikal *et al.*[43], Hornain *et al.*[123] as

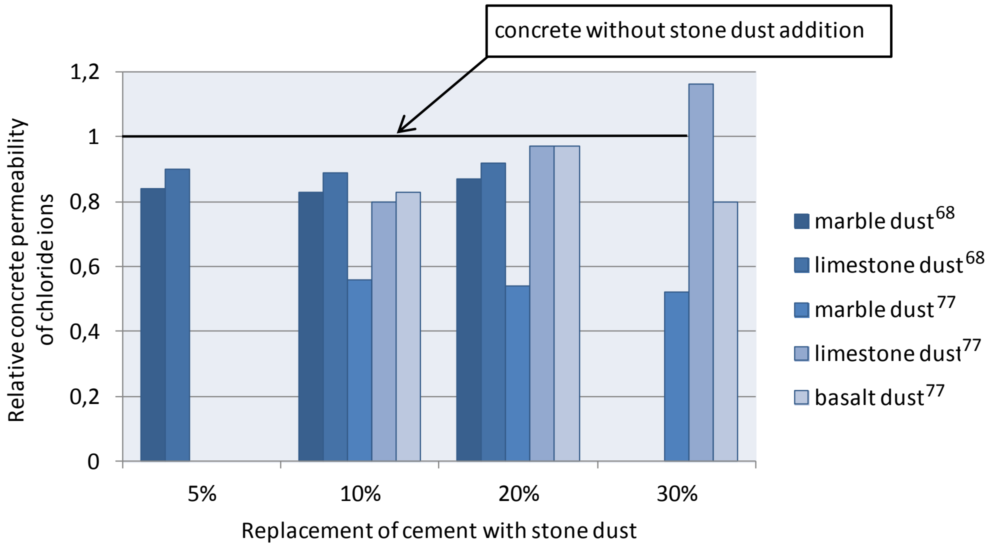

Figure 9. The influence of stone dust on concrete permeability in relation to chloride ions [68, 77].

well as Gesoglu *et al*.[68], who studied concrete with limestone and marble dust additives of finer grain size than cement grains (Figure 9).

Lower porosity and more dense microstructure of cement matrix as well as continuity breakage of pore duct system are important factors that influence the reduction of concrete permeability with filler additives and thus the reduction of chloride ions migration.

One can find some publications on the analysis of concrete resistance with stone dust additives in relation to sulfate aggresiveness. Uysal and Sumer[124] assessed concrete resistance with stone dust additives on the basis of strength decrease of samples stored in sulfate solution relative to samples stored in water. Based on their research, it was found that as stone dust content increased in cement mass, concrete resistance against sulfates also increased. The results obtained by the authors are illustrated in Fig. 10. The positive impact of limestone and marble dust on concrete resistance against sulfates has also been confirmed by Binici *et al*. [66]. In this case, stone dust was used as a partial sand substitute. Porosity and permeability have a great influence on the resistance of cement paste against sulfate corrosion. Thus, the densifying of cement matrix structure with fine particles of stone dust, resulting in lower porosity and permeability, is the main reason for increased concrete resistance with dust additives against aggressive sulfate interaction.

7. CONCLUDING REMARKS

We have shown that waste products can be additives of significant value in cement mortars and cement concretes. The use of waste stone dust in concrete results in improved mechanical parameters and concrete durability. This is primarily due to the physical impact of dust, i.e. concrete structure densification. Chemical activity of some stone dusts in relation to cement clinker phases and their associated effect on cement hydration are also quite important. Due to large specific surface area of dust, there is some deterioration of technological properties of concrete mix. However, recent superplasticizers make it possible to incorporate such a fine dust material into the concrete mix.

Taking into account applicable European standards, stone dusts, except limestone-originated dust, may be used as cement additives in quantities not exceeding 5% cement mass. The content of dusts as mineral

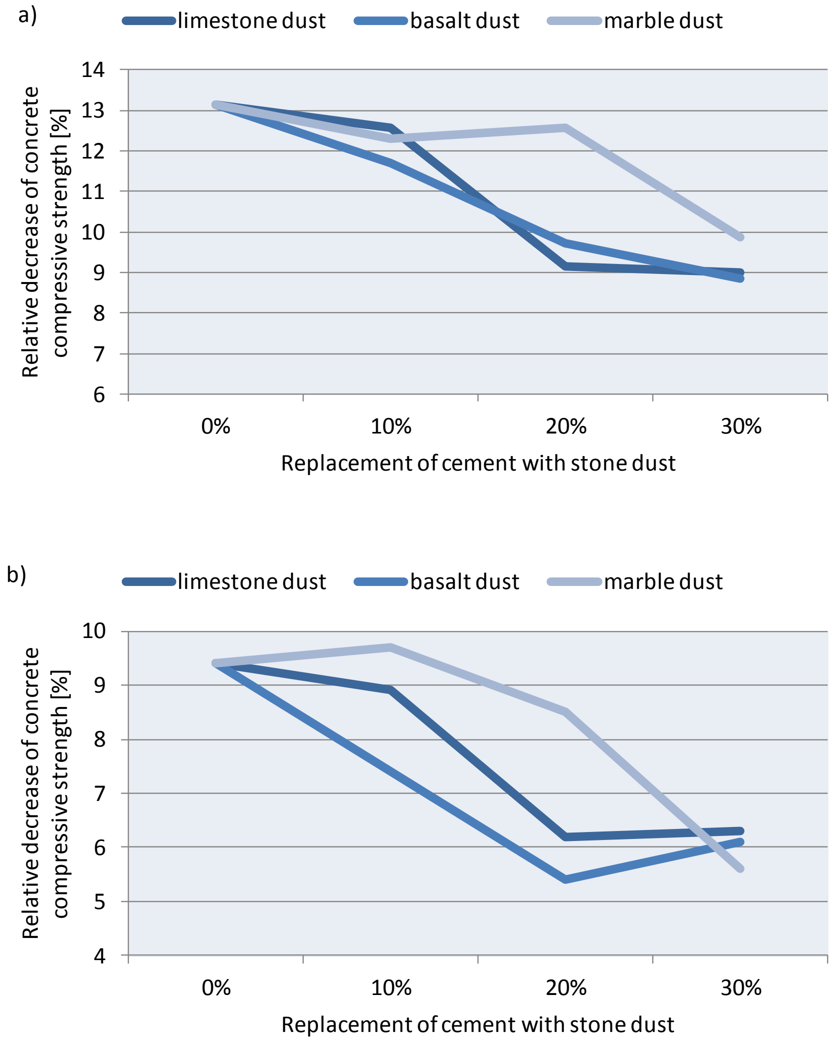

Figure 10. The influence of stone dust on the compressive strength of concrete in sulfate environment: a) samples stored in 10% magnesium sulphate solution, b) samples stored in 10% sodium sulfate solution [124].

fillers in mortar and concrete is determined by the properties of cementitious composites that cannot be degraded as a result of using dust addition. The use of waste stone dust in construction production will not only reduce the cost of concrete production but will also provide efficient management of production waste. Thus, the issues discussed here can be taught in the context of concrete—or else in the context of interaction of materials with the environment [125].

We need to point out that life cycle analysis (LCA) is important and deserves to be used [125]. It is a systems analysis that might lead to the conclusion that in one case recycling, in another re-use and in a third one combustion provide optimal solutions. Students need to be aware that such choices might await them on the job.

Needless to say, given the problems involved in using construction materials—and the sheer amounts of these materials used as noted in the beginning—there is much more that needs to be taught. Also for this reason, this is only the first article in a series.

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