Use of quarry waste in concrete and cementitious mortars

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Thomaida Polydorou[1,2], *Nicholas Kyriakides*[1,2], *Kyriacos Neocleous*[1,2] *and Diofantos Hadjimitsis*[1,2]
[1]Department of Civil Engineering and Geomatics, Cyprus University of Technology, Limassol, Cyprus; [2]ERATOSTHENES Centre of Excellence, Limassol, Cyprus

14.1 Introduction

Circular economy is now fostered in all sectors of industry aiming at sustainable growth and waste reduction, leading to numerous environmental benefits. The idea behind the circular economy concept is to find a new use for materials which have either reached their end-of-life, or are considered as waste. There are numerous interesting research findings (Coppola et al., 2018) that demonstrate the prospects of using waste and end-of-life products in concrete: glass, construction and demolition waste, end-of-life tire rubber, and steel wire and quarry waste can find an alternative use as concrete ingredients, where such nontraditional constituents can modify plain concrete behavior and allow enhanced response to certain types of loading. In addition, reusing such waste and end-of-life materials in concrete is a solution to environmental and health threats posed by their accumulation.

Considering quarry waste specifically, it is widely accepted that accumulation leads to concerning health related issues and significant environmental pollution. Quarry waste is one of the most concerning types of waste, and no reduction of the large volumes generated yearly is foreseen. Quarry waste is generated via the process of stone crushing, amounting to about 1% of the coarse and 2%−5% of the fine aggregate produced. For a rough estimate of the quarry waste quantities accumulating, consider the fact that total aggregate production reaches billions of tons annually.

The possibilities of reusing quarry waste in a meaningful manner are not many. Opportunities rise as researchers further investigate the reuse of waste quarry dust in concrete and cement-based mortars, some of the most widely used materials in the world, used in large volumes and therefore able to absorb large volumes of waste. Introducing waste and end-of-life materials in concrete could thus significantly contribute to elimination of hazardous waste such as quarry waste, which could be used in replacing a fraction of the mixture aggregate content and can even aid in reducing concrete carbon footprint, responsible for 8% of the world's CO_2 emissions since quarry waste is also used in concrete as partial cement replacement.

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14.2 Use of quarry waste in concrete and cementitious mortars

Reusing quarry waste in concrete and cement-based mortar mixtures could provide a solution to the environmental issues caused by quarry waste accumulation. As anticipated, incorporation of waste quarry into cementitious mixtures will lead to altering some of their properties. Depending on the quarry source, mineralogy, and surface properties vary, even for the same type of quarries; furthermore, particle size, quantity of quarry dust, and interaction with other mixture contents are some of the factors that play an important role in mixture properties. Therefore the effects of quarry waste incorporation on concrete and cementitious mortar properties are expected to vary according to previously mentioned factors, thus experimental studies are employed to investigate specific mixtures and conditions.

Incorporation of waste quarry dust as cement replacement is considered to lead to lower compressive strengths in cementitious materials, but research (Kartini et al., 2014) has proven that replacement of cement by waste quarry dust of up to a 15%, while maintaining low water-to-binder ratios, can still produce good quality concrete mixtures (Kartini et al., 2014). In addition, incorporation of waste quarry dust in cementitious composites has also been proven to enhance material properties in certain cases, for example in rubberized concrete, a circular economy inspired material that reuses end-of-life tire products, research (Polydorou et al., 2020) has revealed that waste quarry dust treatment was able to enhance the interfacial transition zone (ITZ) within the composite and thus increase the material compressive strength by over 280%.

Some of the quarry waste sources used in cementitious materials are limestone, silica, quartz, marble, basalt, granite, sand, slate, and gneiss. Limestone is one of the most commonly used quarry waste powders in concrete, but rather in limited quantities due to speculated detrimental effects on both fresh and hardened concrete properties. Interestingly, while addition of limestone quarry waste powders has been observed to decrease both workability and compressive strength in conventional concrete mixtures, in some special cementitious material mixtures, for example self-compacting concrete, limestone quarry waste dust has proven to be favorable to both the rheological and mechanical properties (Felekoglu, 2007).

An overview of the effects of waste quarry dust incorporation in concrete and mortar mixtures on workability, density, compressive strength, flexural strength, splitting tensile strength, water absorption, and chloride resistance are discussed in the following sections.

14.3 Effects of quarry waste on fresh concrete and cementitious mortar properties

14.3.1 Workability

14.3.1.1 General

As expected, incorporation of waste quarry dust as cement or aggregate replacement in concrete or mortars will affect mixture workability, especially when the waste quarry source being introduced has much different surface properties compared to the properties of the material being replaced, as well as when the particle sizes of the quarry waste differ significantly from the particle size of the material being replaced.

In general, previous research have concluded that for specific water-to-cement ratios, waste quarry dust inclusion decreases workability of concrete (Kang et al., 2017), but that could be counteracted by a slight increase in superplasticizer dosage (Rathore et al., 2020).

In previous research (Cohen et al., 2019) where dolomite-based quarry dust particle inclusion was proven to reduce mixture workability, the effect was explained by the asymmetrical rough surface of quarry dust particles compared to the smooth and spherical shape of the fine aggregate being replaced. Less severe workability reduction was reported in mixture cases where same-source quarry dust particles were used to partially replace cement (Cohen et al., 2019).

Inclusion of sandstone quarry waste was also examined as an alternative fine aggregate in concrete, in a study (Rathore et al., 2020) that investigated the effects of including river sand and sandstone quarry waste on fresh and hardened concrete properties of concrete. The study compared workability of mixtures by the amount of additional water and superplasticizer required for maintaining the slump value of the control mix, which included no microfines. As expected, an increase in microfine content implied an increase in superplasticizer content. Sandstone quarry waste particles are angular and have a rough texture, therefore larger surface area, thus require additional water to maintain the desired slump value (Rathore et al., 2020).

In general, aggregate with angular geometry have negative effects on concrete workability. Accordingly, marble quarry waste powders are reported to reduce concrete workability by several studies (Binici et al., 2007; Hebhoub et al., 2011; Shelke et al., 2012; Gameiro et al., 2014).

Nevertheless, when incorporating waste quarry dust in concrete mixtures as partial cement replacement at 10% increments from 0% to 40% of the total cement content in constant water-to-cement ratio mixtures, researchers (Ma et al., 2017) observed an increase in workability with increasing quarry dust content. In this case, findings concluded that the improved workability could be attributed to the fact that quarry dust absorbs less water than cement thus increasing the amount of water available to the dry mix (Ma et al., 2017).

In agreement with other research studies (Ma et al., 2017), concrete workability, in terms of slump, was proven to be positively affected (Kartini et al., 2014) by the addition of waste quarry dust in replacement to cement, in ordinary concrete mixtures, in a research study mixtures of the same water-to-binder ratio, including the same amount of water and the same amount of superplasticizer were compared (Kartini et al., 2014).

14.3.1.2 Self-compacting concrete

Even though addition of typical waste quarry powders in replacement to fine mineral aggregate is believed to decrease workability of conventional concrete, it can actually improve workability in special concrete mixtures. In particular, limestone quarry waste powders were proven (Felekoglu, 2007) to do so by being able to reduce the amount of superplasticizer needed in self-compacting concrete mixtures.

In another study (Schankoski et al., 2020), the rheological properties of self-compacting-concrete mixtures where cement was replaced by quarry waste powders were assessed. The mixtures included limestone, diabase and gneiss quarry waste and were examined under workability tests, rheometry evaluation, and visual observations on surface finish quality. Results indicated that stable fresh concrete mixtures were produced with all three quarry powders as cement replacement. Similar slump flows were achieved in all three cases. Inclusion of either of the three powders in self-compacting-concrete caused reduction of the mixture viscosity in reference to the control mix where no replacement by quarry dust was made (Schankoski et al., 2020).

In addition, the study revealed that limestone and gneiss quarry waste were able to improve self-compacting-concrete passing ability whereas diabase quarry waste powders resulted in lower static segregation compared to limestone (Schankoski et al., 2020).

Rheological evaluation indicated that cement replacement by gneiss quarry waste can decrease yield stress of self-compacting concrete mixtures by about 14%, while cement replacement by limestone and diabase quarry waste powders increased yield stresses by approximately 17%. Comparing with the control mix, researchers (Schankoski et al., 2020) observed a general reduction in viscosity of self-compacting concrete with the addition of waste quarry powders of all three sources (Schankoski et al., 2020). As far as surface finish is concerned, all mixtures achieved acceptable surface finish. The surface finish quality was not affected by type of quarry powder included but by particle size distribution, as expected; finer particles reduced the bug holes area, thus improving surface finish quality. To reduce the area of bug holes and ensure adequate finish quality, researchers (Schankoski et al., 2020) suggested grinding quarry waste to reach particle sizes in proximity of cement particle size. In general, it was proven that self-compacting concrete mixtures including diabase and gneiss quarry waste powders are feasible without much variance in fresh concrete properties compared to self-compacting concrete mixtures including limestone or simply cement (Schankoski et al., 2020).

The effects of including quarry dust on the workability of self-compacting concrete were investigated by another study (Ho et al., 2002), where four mixtures were compared. Each one of the four mixtures included either granite fines or limestone powder at 35% or 50% of the total powder content by weight. Granite and limestone fines were obtained from concrete aggregate producing quarries. To maintain similar flow, the mixtures made with granite fines required about 25% more superplasticizer compared to their equivalent mixtures made with limestone powder at the same content (Ho et al., 2002), while indicating that the granite fines used were finer than the limestone particles and due to their nature, more flaky and elongated (Ho et al., 2002), highlighting the fact that effects on concrete rheology vary according to the physical properties of the fine particles included. Especially since waste quarry dusts are used, variance is expected over time even from quarry dust obtained from the same source (Ho et al., 2002).

14.3.1.3 Ultrahigh-performance concrete

It is generally accepted that concrete workability can increase when cement is substituted by quarry dust. In ultrahigh-performance concrete, both basalt powder and limestone powder increased flow significantly, limestone powder to a higher extend than basalt (Yang et al., 2020). The workability increase is explained by the dilution effect and in particular by the fact that quarry dust particle size distribution is different than that of the replaced cement; quarry waste powders include less particles in the range of 0−10 μm particle size, therefore absorb less water than cement. Even in comparison between quarry sources, limestone is able to further increase concrete workability than basalt due to its lower cumulative content of finer particles (Yang et al., 2020). In addition, mineralogical and surface properties play a role in water absorption and consequently mixture workability (Schankoski et al., 2017), in this case basalt absorbs more water than limestone due to its porous surface, thus workability is lower when cement in replaced by basalt than when replaced by limestone quarry powder.

14.3.1.4 Cementitious and geopolymer mortars

A reduction in workability was observed in fly ash alkali-activated geopolymer mixtures with increasing quarry dust content, especially at higher than 20% fly ash replacement by waste quarry dust, possibly due to the rough and asymmetrical particle shapes of quarry dust as opposed to smooth and round fly ash particles being replaced (Cohen et al., 2019). Less severe reduction was reported in the workability of conventional Portland cement mortar, with the addition of waste quarry dust in replacement to cement. It should be noted that mixture preparation in both fly ash geopolymer and conventional Portland cement mortar mixtures was based on a constant water-to-binder ratio for consistency and considering only the fly ash content as binder content in the geopolymer mixtures as well as only the cement as the binder in cement-based mixtures. Therefore, with increasing quarry dust incorporation, the total water to dry solids ratio is reduced, thus the cement mortar mixtures ended up including more water compared to the fly ash geopolymer mixtures in terms of water to dry solids ratios. Despite that, higher workability values were achieved by the fly ash mixtures compared to cement-based mixtures for waste quarry dust incorporation of up to 20%. As expected, due to the higher water to dry solids ratios, workability of cement-based mixtures was higher than the workability of fly ash geopolymer mixtures including the same percentage in waste quarry dust, for replacement contents greater than 20% (Cohen et al., 2019). With increasing waste quarry dust content, workability of Portland cement mortar is also reduced as the water to dry solids ratio is lowered with the addition of quarry dust, but not as severely as observed for the geopolymer mixtures, since both quarry dust particles and cement particles have asymmetrical shapes (Cohen et al., 2019).

The effects of quarry dust inclusion in geopolymer mixtures were also investigated by incorporation of either 100% quarry dust or quarry dust mixed with silica sand (one-third sand and two-thirds quarry dust), as mineral filler in mixtures where fly ash was used as binder. Sodium silicate solution and three different molarities (3M, 6M, and 12M) of sodium hydroxide NaOH were used as alkali activators. Curing occurred at 80°C in an oven and lasted 1 h, 3 h, and 5 h (Kürklü and Görhan, 2019).

A decrease in workability was indicated for the higher quarry dust content mixtures. Silica sand, which is coarser than quarry dust, reduces yield stress in the fresh mixtures, therefore increases workability (Kürklü and Görhan, 2019). For the fly ash–based geopolymer mixtures investigated, using 100% quarry dust as mineral filler was disadvantageous to rheological properties (Kürklü and Görhan, 2019).

14.4 Effects of quarry waste on hardened concrete and cementitious mortar properties

14.4.1 General

Just like fresh concrete properties, hardened concrete properties are also altered when waste quarry dust is included in concrete and cement-based mortar mixtures. Research findings are presented in the following sections and describe the effects of including waste quarry dust on the mechanical properties of concrete and mortar mixtures.

In general, addition of waste quarry dust up to a certain content in conventional concrete, has been shown to improve the mechanical properties of the material. Research have proven that incorporating very fine waste quarry particles in the range of 10%–20% (Rathore et al., 2020) of the total fine aggregate content of a concrete mixture can increase the 28-day compressive, tensile, and splitting tensile strength of concrete. Researchers agree that waste quarry dust at 20% (Imran and Muthu, 2018) sand replacement can increase the compressive and flexural strength of concrete by 10% and splitting tensile strength by 15%.

Many studies investigated the effects of waste quarry dust incorporation as a replacement to ordinary Portland cement, with researchers, (e.g., Kartini et al., 2014; Rathore et al., 2020; Imran and Muthu, 2018), reporting that at certain percentages, incorporation of quarry dust in concrete as part of the pozzolan content enhances hardened mechanical properties of concrete (in addition to fresh rheological properties).

Furthermore, a study (Thapa et al., 2019) investigated gravel wash mud powder obtained from gravel quarrying waste as a supplementary cementitious material in conventional concrete. After the waste gravel was calcinated, researchers confirmed pozzolanic activity and concrete strength enhancing ability even when incorporated in low contents in concrete and cementitious mixtures (Thapa et al., 2019).

The effects of waste quarry dust were also investigated in ultrahigh-performance concrete mixtures (Yang et al., 2020), where outcomes led to the suggestion that cement replacement by waste quarry dust is actually more meaningful in ultrahigh-performance than conventional concrete mixtures. In specific, basalt and limestone powders were used as cement replacement at 22.2% and 44.4% in the development of economic and environmentally friendly ultrahigh-performance concrete to examine workability, mechanical properties, durability, shrinkage, hydration kinetics, electrical resistivity, pore structure, and CO_2 emission index of the material (Yang et al., 2020).

The effects of quarry waste incorporation have also been considered in what is called foam concrete, a cementitious mortar slurry made with river sand and including foam at a maximum 10% by volume (Gopalakrishnan et al., 2020). This lightweight cementitious material is made with conventional cement, fine aggregate, foaming agent and compressed air, in a variety of densities according to foaming type, typically ranging between 400 and 1600 kg/m^3 (Risdanareni et al., 2016). Foam concrete is a thermal and sound insulating material with improved freeze-thaw resistance that requires little to no compaction and is preferred for producing floor screeds, roof insulation, building blocks, and subbase layers in roads. To produce more economical and ecological lightweight foam concrete mixtures, and specifically to reduce the use of river sand, replacement by industrial quarry waste is suggested. The use of waste quarry dust to partially replace river sand was investigated (Gopalakrishnan et al., 2020) by studying the effects on the properties of lightweight foam concrete at five contents, starting at a 10% replacement and up to 50% replacement at 10% increments, in mixtures with only cement included as binder. In additional trial mixtures, river sand replacement by quarry dust was investigated in combination with cement replacement by fly ash, both at equal replacement ratios between 10% and 50% at 10% increments. While the mixtures where only river sand was replaced indicated inferior mechanical properties than the control mix, the mixture where both 30% of the cement and river sand were replaced by fly ash and quarry dust, respectively, had superior mechanical properties than the control mix. In specific, while maintaining a slightly lower density compared to the control mix, the optimum mixture had higher compressive and tensile strengths (Gopalakrishnan et al., 2020). The effects of waste quarry dust on the hardened concrete properties of lightweight foam concrete are discussed in the following sections.

14.4.2 Density

In a lightweight foam concrete study, sample densities were obtained for mixtures where river sand, the type of aggregate usually included in these lightweight cementitious mortar mixtures was replaced by quarry dust (Gopalakrishnan et al., 2020). A 2.30% decrease in foam concrete density was observed for 10% river sand replacement, and as expected, increasing waste quarry dust content led to decreasing foam concrete densities to a maximum 6.14% reduction in density for the 50% replacement (Gopalakrishnan et al., 2020). For the mixtures where both river sand and cement were partially replaced by waste quarry dust and fly ash respectively, density values for the 30%, 40%, and 50% replacement percentages were very close to the reference mix value, specifically the case where 40% of the cement was replaced by fly ash and 40% of the river sand was replaced by quarry waste (Gopalakrishnan et al., 2020). It should be noted that when only cement is replaced by fly ash, density is reported to experience a decrease with increasing fly ash content, and the same is indicated for the cases where only river sand is replaced by waste quarry dust.

Interestingly, this is not the case when both cement and river sand are concurrently partially replaced by fly ash and waste quarry dust respectively. In mixtures where partial replacement applied to both cement and river sand content, although an initial drop in density was observed for the 10% replacement case, a continuous increase in density is reported with increasing replacement up to the 40% replacement, reaching

99.8% of the density of the control mix. A further increase to 50% replacement of both cement and river sand by fly ash and quarry dust respectively leads to a slight decrease that lowers the material density down to 99.4% of the control mix density (Gopalakrishnan et al., 2020).

14.4.3 Compressive strength

14.4.3.1 General

A 10% increase in compressive strength was observed in concrete mixtures with a 20% sand replacement by waste quarry dust (Imran and Muthu, 2018).

Inclusion of dolomite-based waste quarry dust in cement-based materials was able to increase compressive strength by 10%−45% and was explained by the fact that the asymmetrical shape of quarry dust particles improves mechanical anchoring within the fine aggregate matrix of the mixture (Cohen et al., 2019).

The compressive strength of concrete with waste quarry dust included as cement replacement was evaluated at 7, 14, 28, 60, 90, and 120 days. In general, lower compressive strengths were obtained compared to their equivalent reference mix, as the waste quarry dust content increased for the constant water-to-binder ratio mixtures. Nevertheless, the 28-day compressive strength of the 0.3 water-to-binder ratio with 3% of its cement content replaced by quarry dust was comparable to that of the reference mix. Similarly, the 60-day compressive strength of mix where 3% of the cement was replaced by waste quarry dust within the 0.4 water-to-binder ratio mixtures, was closer to the 60-day compressive strength of the reference mix with 0.4 water-to-binder ratio. In general, the compressive strength reduction observed with increasing waste quarry dust content is more evident in the higher water-to-binder ratio mixtures.

Researchers (Rathore et al., 2020) were able to increase the compressive strength of concrete by including sandstone quarry waste up to a certain content, in replacement of fine aggregate. The compressive strength was reduced when sandstone fines were added to the mix in higher contents, explained by the fact that up to a certain percentage, replacement of aggregate by quarry waste microfines fills the voids within the matrix and results in a denser mix. Beyond that percentage, additional microfines lead to a reduction in compressive strength due to significant increase of surface area, resulting in weaker bonding if no additional cement is provided (Rathore et al., 2020). The ideal sandstone quarry waste content in terms of improving the compressive strength of concrete in this particular study was 20% replacement of the fine aggregate content (Rathore et al., 2020).

In studies where waste quarry dust was used to replace cement, a slight decrease in compressive strength was reported when quarry dust was used to replace 20% of the mixture cement content, in comparison to the control mix, where no quarry dust was included. Higher decrease in compressive strength was reported when 10% of the cement was replaced by waste quarry dust. When higher quarry dust content was included in concrete, beyond the 20% cement replacement content, the compressive strength decreased further with increasing quarry dust content (Ma et al., 2017).

14.4.3.2 Self-compacting concrete

Previous research (Felekoglu, 2007) has shown that limestone quarry waste inclusion in self-compacting concrete mixtures could increase self-compacting concrete 28-day compressive strength, reducing the cost of self-compacting concrete in terms of unit compressive strength by 0.05−02$/MPa/m^3 (Felekoglu, 2007).

14.4.3.3 Lightweight foam concrete

In lightweight foamed concrete mixtures, the compressive strength and general strength performance of concrete improved when river sand was replaced by quarry dust (Kang et al., 2017).

Replacement of river sand by quarry waste in lightweight foam concrete with cement being the only binder included in the mix, led to a reduction in compressive strength in the range of 11.6% for the 10% replacement to 39.9% for the 50% replacement (Gopalakrishnan et al., 2020). Compressive strength was reduced with increasing quarry dust content in the case where 100% of the binder content was cement. Interestingly, 27.55% higher compressive strength than that of the reference mixture was reached by the mix where 30% of the cement was replaced by fly ash concurrently with 30% of the river sand being replaced by quarry dust. In addition, for the 20% and 40% replacement combination (both cement being replaced by fly ash and river sand being replaced by quarry dust), the compressive strengths were within 5% of the compressive strength of the control mix (no cement or river sand replaced) (Gopalakrishnan et al., 2020).

14.4.3.4 Ultrahigh-performance concrete

In a study (Yang et al., 2020) where basalt and limestone quarry waste powders were incorporated into ultrahigh-performance concrete mixtures in an attempt to produce more sustainable, environmentally friendly ultrahigh-performance concrete, 22.2%, and 44.4% of the mixture cement content was replaced by either limestone or basalt quarry waste and their compressive strengths at 7, 28, and 56 days were compared to those of the reference mix. As expected, lower compressive strengths were reached by mixtures including waste quarry dust as cement replacement, with the 56-day strength of ultrahigh-performance concrete including basalt quarry waste dust at a 44.4% replacement of the total cement content strength suffering a 10.3% (Yang et al., 2020) reduction compared to the control mix. On a positive note, in the equivalent case of the same replacement content by limestone quarry waste powder replacement, the 56-day strength of the mixture did not vary significantly from the 56-day compressive strength of the control mix (Yang et al., 2020).

It should be noted that while the seven-day compressive strengths of all mixtures including quarry waste powders are much lower than the seven-day compressive strength of the reference mix, further hydration process allows mixtures including waste quarry dust to improve their compressive strength and reach values closer to the reference mix compressive strength by 28 and 56 days (Yang et al., 2020). This phenomenon is explained by the pozzolanic activity of the waste quarry particles that happens later, leading to densification of the material microstructure (Korpa et al., 2009), further proving that ultrahigh-performance concrete can be developed with the successful inclusion of waste quarry dust as partial cement replacement, leading to a more economical and environmentally friendly material without compromising strength.

Waste quarry dust can partially replace cement even in ultrahigh-performance concrete, and although noteworthy at seven days, the decrease in long term compressive strength is insignificant (Yang et al., 2020). It was pointed out that in ultrahigh-performance concrete mixtures, the level of cement hydration is limited to around 30%–40% (Korpa et al., 2009), therefore, unhydrated cement that serves simply as a filler can be replaced by other fine powders for sustainability and economy (Yang et al., 2020), particularly by waste quarry dusts from aggregate manufacturing, consequently also reducing the harm to the environment caused by their accumulation. Not only that, but inclusion of waste quarry dust in ultrahigh-performance concrete was able to reduce autogenous shrinkage up to 33.6% (Yang et al., 2020), which is a promising outcome considering that ultrahigh-performance concrete is prone to early-age cracking; indicating that quarry waste incorporation in ultrahigh-performance concrete mixtures could be the solution to their dimensional stability issue (Yang et al., 2020). In terms of general mechanical properties, limestone quarry waste is a superior cement replacement quarry source in ultrahigh-performance concrete mixtures compared to basalt quarry waste (Yang et al., 2020).

14.4.3.5 Cementitious and geopolymer mortars

Similarly in mortar mixtures, dolomite-based waste quarry dust was able to increase compressive strength significantly, in both cases where waste quarry dust was used to partially replace cement in cementitious mortar or fly ash in geopolymer mortar (Cohen et al., 2019). It was observed that in either case, waste quarry dust had significant effects on fresh and hardened properties of the mixtures (Cohen et al., 2019). Most interestingly, calorimetry results indicated that dolomite-based waste quarry dust was able to enhance the hydration reaction process in cementitious mortars, explained by the fact that smaller particles act as nucleation points therefore leading to faster and more complete hydration (Cohen et al., 2019).

Furthermore, waste quarry dust was used to partially replace cement in ordinary Portland cement mortar, while also used in parallel to partially replace fly ash in an alkaline activated geopolymer mixtures, aiming to generate environmentally friendly materials without compromising strength. The same quarry dust source was used in both cement replacement in conventional cementitious binder paste and fly ash replacement in geopolymer mixtures, ranging from 0% to 40% by weight, at 10% increments (Cohen et al., 2019). Fresh mixture flow, compressive strength, thermal expansion, and acid resistance of the samples were some of the properties evaluated. A significant improvement of the compressive strength was observed for both ordinary concrete and the geopolymer mixture studied. Researchers (Cohen et al., 2019) used two mechanisms to explain this phenomenon.

Firstly, for the case of the fly ash alkali-activated geopolymer, incorporation of waste quarry dust particles which are rough and asymmetrical, in replacement to the smooth and round fly ash particles, leads to improved mechanical anchoring of the particles within the matrix therefore leading to improved mechanical performance.

The second mechanism suggest that improved mechanical properties are initiated by the enhanced hydration reaction, as perceived by calorimetry readings, mainly for the cement-based mixtures. This denotes that the quarry dust fine particles serve as nucleation points and thus lead to faster comprehensive hydration, rather than the quarry dust acting as a reactive additive in the mixture (Cohen et al., 2019).

Waste quarry dust incorporation, and in particular limestone and dolomite quarry waste, have also been investigated in geopolymer mixtures, in most cases as aggregate replacement and less commonly as partial replacement to geopolymeric binder (Cohen et al., 2019). In metakaolin-based geopolymers, aggregate replacement by limestone or dolomite waste quarry dust was investigated (Yip et al., 2008) and at a content of 20% by weight, led to an increase in compressive strength, but incorporation of waste quarry dust at higher contents was detrimental to the compressive strength of geopolymer mixtures. This fact was explained by the excess quarry dust interfering within the gel formation process (Yip et al., 2008). It was also noted that in the case of metakaolin-based geopolymer mixtures, limestone quarry dust incorporation led to higher strengths than dolomite quarry dust (Yip et al., 2008).

Research (Moseson et al., 2012) has also revealed that including higher quantities of quarry dust in geopolymers, specifically 40% by weight of limestone powder in a dry mix of slag and sodium carbonate activated in water produced high compressive strength mixtures reaching 46 MPa at 3 days maturity and 61 MPa at 28 days, pointing out the environmental and economic benefits of using waste quarry dust in construction materials in general as well as the increased sustainability of geopolymers (Cohen et al., 2019).

14.4.4 Flexural strength

Similarly with compressive strength observations, researchers who investigated the effects of sandstone quarry waste being used in replacement of fine aggregate in concrete reported an increase in flexural strength with increasing sandstone content up to a certain point. Further sandstone microfine content decreased concrete flexural strength. The sandstone quarry waste particles have rough texture and more angular shape, therefore facilitate enhanced bonding between the aggregates and the cement paste, further leading to higher strength (Rathore et al., 2020). The highest flexural strength in this study was reached by a mixture that included sandstone quarry waste dust at a content of 10% of the control mixture fine aggregate(Rathore et al., 2020).

In addition, a 10% increase in flexural strength was observed in concrete mixtures which included a 20% sand replacement by waste quarry dust (Imran and Muthu, 2018).

14.4.5 Splitting tensile strength

The effects of including sandstone quarry waste microfines on the splitting tensile strength follow the trend observed for the compressive and flexural strengths. Inclusion of sandstone fine particles up to a certain content increased the splitting tensile strength of concrete, but decreased with further increase of the sandstone quarry waste content (Rathore et al., 2020). The highest splitting tensile strength observed in the study was when sandstone waste quarry microfines were included in the mix in replacement of 15% of the fine aggregate content (Rathore et al., 2020).

Similarly, a 15% increase in splitting tensile strength was observed in concrete mixtures with a 20% sand replacement by waste quarry dust (Imran and Muthu, 2018).

In contrast, in the case of lightweight foam concrete, a reduction in splitting tensile strength was reported with increasing quarry waste in replacement to river sand. In particular, a 10% replacement of river sand by quarry waste led to 19.2% decrease in splitting tensile strength. At higher replacement percentages, the splitting tensile strength was reduced further up to a 58% reduction for the case where 50% of the river sand was replaced by quarry waste. In contrast, for the combined 30% replacement of each cement and river sand by fly ash and waste quarry dust respectively, the splitting tensile strength was increased by 4.8% compared to the reference mix (Gopalakrishnan et al., 2020).

14.4.6 Water absorption

Water absorption of concretes including waste quarry dusts were studied (Gameiro et al., 2014) in terms of water absorption by capillary action and in terms of water absorption by specimen immersion in water. In terms of capillary action, research (Gameiro et al., 2014) has shown that inclusion of marble quarry waste had a positive effect on water absorption. In particular, a reduction in capillary action was observed, especially at replacement ratios between 15% and 30% (Gameiro et al., 2014; André et al., 2014) and was attributed to enhanced bonding of the aggregate to the cement paste, due to the angular and elongated geometry of the fine marble waste aggregate (Gameiro et al., 2014). Beyond the 30% replacement ratio, researchers (Binici et al., 2007; Hameed and Sekar, 2009; Corinaldesi et al., 2010) observed negative effects on water absorption due to a general increase in concrete porosity.

In terms of water absorption by immersion, researchers (Gameiro et al., 2014) concluded that marble waste quarry incorporation was able to reduce specimen water absorption thus improving concrete durability.

In general, for mixtures where fine aggregate was substituted by quarry dust for sustainability, researchers observed a decrease in water absorption with increasing waste quarry dust content (Imran and Muthu, 2018).

In contrast, for the case of lightweight foam concrete, an increase in water absorption was reported (Gopalakrishnan et al., 2020) for increasing quarry dust content as partial replacement to the mixture total content of river sand. The amount of water absorbed is directly related to the density, which also relates directly to 28-day compressive strength reached by the mixture, therefore the optimum mix in terms of compressive strength in this study, had the lowest water absorption. In lightweight foam concrete, a 30% combined replacement of cement by fly ash and river sand by quarry dust, led to lower water absorption compared to the control mix (Gopalakrishnan et al., 2020).

Even though cement replacement by waste quarry dust leads to increased water absorption in ordinary concrete, it is still possible to develop good quality concrete mixtures of low permeability, by including waste quarry dust at a content of up to 15% cement replacement and maintaining low water-to-binder ratios (Kartini et al., 2014).

The durability related effects of using waste quarry dust in ordinary Portland cement mortar and fly ash alkali-activated geopolymers to increase sustainability of the mixtures were examined through thermal expansion and acid resistance (Cohen et al., 2019).

Due to the high magnesium content of the waste quarry dust used in this case, since it is mainly of dolomite content, the developed materials are prone to alkali-carbonate reaction (Cohen et al., 2019). Alkali-carbonate reaction makes cementitious materials prone to structural degradation, since it causes the hardened samples to expand, due to an increase in volume that is caused by the chemical reaction products. To assess the potential of materials to degrade due to alkali-carbonate reaction, alkali-related expansion was measured as directed by relevant specifications, comparing expansion of the cement-based and geopolymer mixtures that included the largest quantities of waste quarry dust (40%) to their equivalent reference mixtures, i.e., those including no waste quarry dust. Results indicated expansions within the 0.1% limit for all mixtures (Cohen et al., 2019), therefore all of them fall in the nonalkali reactive category as classified by the relative assessment method expansion limits (Hooton and Rogers, 1993). Additional measurements revealed that no magnesium hydroxide or other new phases that could have caused expansion formed in the hardened mixtures (Cohen et al., 2019).

Specifically, for the cement-based mixtures, assessment indicated no significant increase in alkali expansion with the inclusion of waste quarry dust as a replacement to 40% of the cement content. In addition, comparison of alkali expansion assessment between cement-based and fly ash geopolymer mortars revealed lower expansion values for the fly ash–based geopolymers than the conventional Portland cement mortar mixtures. In general, this was explained by the possibility that the alkali activation reaction continues as long as the alkalinity in the pore solution remains high, and that leads to densification of the geopolymer mixture matrix thus decreasing permeability and enhancing mechanical properties, in agreement with the phenomena explained in previous studies, where enhanced chemical and thermal durability of geopolymers was discovered (Davidovits, n.d.; Lloyd et al., 2012; Bernal and Provis, 2014).

As it is known, cementitious materials are prone to acid attack due to their alkalinity, and experience even quicker degradation in the presence of sulfate ions due to sulfate attack (Allahverdi and Škvára, 2000). In contrast, geopolymer materials are considered resistant to acidic conditions and sulfate attack (Lloyd et al., 2012; Provis, 2014). The effects of incorporation of waste quarry dust on the acid resistance of cement-based and fly ash–based geopolymer mortars were assessed through testing, following immersion of hardened mortar specimens ($5 \times 5 \times 5$ cm cubes) in static 5% sulfuric acid solution for 120 days (Cohen et al., 2019).

Considering the reference mix specimens (no quarry dust included), the cement-based sample experienced visible deterioration, losing about 50% of its volume and had a measured weight loss of 30%. In contrast, the fly ash–based geopolymer sample did not present significant deterioration after 120 days in sulfuric acid solution. With waste quarry dust incorporation in replacement to 40% of its cement content, the cement-based mortar specimen experienced greater deterioration, at 36% weight loss, 6% higher than its equivalent reference mix specimen. However, and even though a higher weight loss was observed, waste quarry dust incorporation in cementitious mortar caused the formation of gypsum layers on the sample surface which led to delayed dissolution (Cohen et al., 2019).

Interestingly, the fly ash−based geopolymer sample that included quarry dust in replacement to 40% of its fly ash content underwent such rapid disintegration after exposure to sulfuric acid that researchers were not able to measure its weight loss (Cohen et al., 2019). This led to a conclusion that the quarry dust sources investigated lead to an increasing acid sensitivity of the studied mixtures, even for the fly ash−based geopolymer specimens which were otherwise not susceptible to acid attacks. This is backed up by knowing the mineral nature of the quarry dusts used in this study, dolomite and calcite, which are known to be subtle to acidic environments (Cohen et al., 2019). The study proves that dolomitic quarry dust cannot be used in cementitious or geopolymeric mortars that will be exposed to acidic environments (Cohen et al., 2019).

14.4.7 Chloride resistance

The durability of ultrahigh-performance concrete mixtures with waste quarry dust included as cement replacement was assessed by the Coulomb electric flux method (Yang et al., 2020) for determining chloride ion penetrability based on charge passing. Results demonstrated an increasing charge, therefore increasing ion penetrability and thus decreasing durability, with increasing quarry waste content. In particular, when 22.2% of the cement content was replaced by basalt quarry powder, an almost 86% increase in charge was reported, compared to the reference mixture total charge, while for a 44.4% cement replacement by basalt quarry powder, the total charge increased by nearly 166%. The increase in mixture total charge was not as profound when 22.2% and 44.4% of the cement was replaced by limestone quarry dust; 28.57% and 128.57% increases respectively were observed (Yang et al., 2020).

Considering that ultrahigh-performance concrete mixtures are far more durable than conventional concrete, even the highest increase in mixture total charge as examined by the Coulomb electric flux method is only 93C (Yang et al., 2020), still indicating negligible chloride ion penetrability based on charge passed, therefore much higher durability compared to conventional concrete mixtures.

Interestingly, when tested for chloride resistance, conventional concrete specimens with waste quarry dust incorporated in replacement to fine aggregate, displayed best results in terms of resistance to chloride penetration at a 20% sand replacement content (Imran and Muthu, 2018).

14.5 Conclusion

Quarry waste powders can be successfully used in concrete and cementitious mortars either as cement replacement or in replacement to the traditionally used fine mineral aggregate. The quarry source and quarry dust particle size will affect mixture properties both in terms of fresh and hardened concrete properties as well as durability. Surface characteristics of the quarry dust being incorporated as well as the surface characteristics of the material being replaced will be the main elements influencing mixture workability. As explained herein, replacement by quarry waste particles with asymmetrical rough surface or angular geometry, which absorb more water, reduces workability. In terms of hardened concrete properties, quarry source and particle size play an important role. Using a variety of particle sizes can aid in creating denser material matrix, which consequently improves mechanical properties. Certain quarry sources can enhance concrete and cementitious mortar mechanical properties solely due to their nature, for example pozzolans, but as expected, cement replacement by waste quarry dusts at higher percentages can be detrimental to hardened concrete properties. At certain content, waste quarry dust incorporation can reduce concrete and cementitious mortar water absorption thus improving durability. It is evident that well thought mix designs can consume quarry waste materials in favor to concrete properties while at the same time promoting sustainability and reducing the accumulation of dangerous waste.

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