Quarry Dust: The Potential of By-Product Waste as Sulfate Attack Resistance in Cement Composites

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Abstract
In this study, the durability of cement composites at 0 wt.%, 12.5 wt.%, and 17.5 wt.% of the addition of quarry dust was investigated against sulfate attack at 1,2,3,4,8,13 and 15 weeks. The specimens of cement composites were immersed in sodium sulfate solution and evaluated for length change and salt deposition. Cement composites with the addition of 12.5 wt.% of quarry dust were found to possess the best sulfate attack resistance. The sodium sulfate solution was found not to affect the original length of the cement composites at all percentages of quarry dust. A visual examination revealed that the cement composites without the addition of quarry dust showed the existence of salt deposition compared to 12.5 wt.% and 17.5 wt.%. The quarry dust consumption presented the cement composites' durability improvement due to sulfate attack. The silica content and filing effect of quarry dust chemically react with the calcium hydroxide released by ordinary Portland cement to form durable cement composites.

Keywords: cement composites, sulfate attack, quarry dust

1.0 Introduction

The rapid movement in economic sectors in the modern century increases energy and resource consumption, including in the construction industry. The production of many types of merchandise by the factories will enhance the solid or by-products waste that increases disposal problems, contributed the various environmental issues, and cause serious health hazards. The aim of environmental agencies and governments all over the world is to minimize the problems of disposal and health hazards of these wastes and by-products. In recent years, the management of solid waste is a challenge for civil and environmental engineers to utilize economically supplementary cementitious materials produced at a reasonable cost with a low possible environmental impact (Smita and Rubina, 2008). Thus, utilizing industrial waste and by-products by productively turning them, especially in the construction industry can contribute to sustainable development. Because of environmental and economic reasons, there has been a growing trend for the use of industrial wastes or by-products as supplementary material in the production of concrete (Gidley and Sack, 1984). Many types of research have been conducted to recycle valuable material and reduce the volume of hazardous solid waste and other pollutants that harm living organisms (Smita and Rubina, 2008). Several types of industrial wastes or by-products can be utilized in the construction industry either as a full or partial replacement of cement, sand or as an additive material such as fly ash, ground granulated blast furnace slag, metakaolin, waste glass, quarry dust, wood ash and so on. In the way to reduce the consumption of raw materials and waste management issues, the paper promotes the utilization of quarry dust as a partial sand replacement substituted with ordinary Portland cement without neglecting the strength properties of the cement composites. Lately, the utilization of quarry dust as a partial or full replacement of sand in the construction industry has been growing rapidly to overcome the problems issued by waste.

For this reason, this paper aims to reveal the effects of sulfate attack on cement composites with the addition of quarry dust in certain percentages in durability studies. This assessment was conducted in a durability study that continued from the previous phases, namely proportioning and characterization studies. The suitable weight percent of quarry dust was obtained from proportioning study according to the results of cement composites' physical and mechanical properties. According to the results, the characterizations of the samples were determined by studying the crack profile, fracture, and surface morphology of cement composites. Finally, in the durability study, the samples were prepared and immersed in sodium sulfate solution to investigate the effects of quarry dust on cement composites due to sulfate attack. Besides the physical and mechanical properties, the durability of cement composites also has an important role in masonry structures. It should be noted that durability is the ability to last a long time without significant deterioration. A durable material helps the environment by conserving resources and reducing wastes and the environmental impacts of repair and replacement (Portland Cement Association, 2022).

2.0 Literature Review

The term sulfate attack denotes an increase in the volume of cement paste in concrete or mortar due to the chemical action between the hydration of cement and solution containing sulfates. During the exposure occurs, the sulfate solution is likely to react with hydrated C_3A in the hardened cement paste to form a new chemical compound called ettringite, which can cause the expansion and disruption of the concrete or mortar (Shetty, 1986). The compound tricalcium aluminate (C_3A) hydrates very rapidly, produces a considerable amount of heat, has less resistance to chemical attack, and has the greatest tendency to cause cracking due to volume changes (Murdock et al., 1991). This statement is also supported by Hossack and Thomas (2015), which stated the formation of ettringite causes expansion and cracking of the hardened cement paste, followed by the formation of thaumasite which disintegrates the calcium-silicate hydrates (C–S–H) structure, thus damaging the concrete and compromising its long-term durability. Sulfate attack can manifest in the form of expansion and cracking of the concrete or cement composites, which increases the permeability and aggressive water penetrates more easily into the interior thus accelerating the process of deterioration. The cementitious structures may suffer from degradation due to the formation of crystallization pressure when subjected to salt attack or exposed to an aggressive environment during their service life. Jordan (2001) suggested that the durability of the structures is affected by their ability to resist the cycles of heat and cold, wetting and drying, and the absorption of various contaminants from their environment. In addition to this, the most potentially destructive weathering factor is freezing and thawing while the cement composites are wet, particularly in the presence of deicing chemicals (Portland Cement Association, 2022). Deterioration is caused by the freezing of water and subsequent expansion in the cement paste, aggregate particles, or both. On the other hand, contaminants, particularly salts, can physically and chemically attack masonry.

Nevertheless, not all the salt that exists in the moisture will cause damage or even be liable to attack. According to Bederina et al (2013), the most aggressive chemicals that can affect the durability of concrete and mortar structures are sulfates and chlorides. Meanwhile, the higher concentration of sulfates in the groundwater is generally due to the presence of magnesium, sodium, and potassium sulfates (Mehta and Monteiro, 2006). This is undoubtedly supported by Zsembery (2001) that the most problematic salt attacks are sodium sulfate and magnesium chloride, which tend to attract and absorb water.

Previously, Lee et al (2008) and Santhanam et al (2002) explored the effect of sodium and magnesium sulfate on masonry mortar. From the findings of Lee et al (2008), the mortar specimens deteriorated due to sulfate attack after 15 months cured into the solution and the result showed surface damage and a reduction in the compressive strength. Besides that, the expansion of mortar specimens that were exposed to magnesium sulfate solution was lower than in sodium sulfate solution. This situation is explained by Al Amoudi et al (1995) that in different pH environments, the sulfate expansion properties are related significantly to the stability of the products formed by sulfate attack.

Mortars are very widely used in the construction of harbors, docks, jetties, and other marine structures frequently suffer due to attacks of dissolved chemicals on the product of hydration, crystallization of salts, and extreme exposure to various acids during their service life. In the marine environment, the application of ordinary Portland cement was not showing good resistance against the sulfate attack. Sulfate-resisting Portland cement has a better performance in resisting sulfate attack than ordinary Portland cement due to the reduction in the tricalcium aluminate (C_3A) content as well as the high silicate content (Shetty, 1986). The consumption of special materials such as sulfate-resisting Portland cement contributed to the high expenses in the construction.

According to other findings, the addition of pozzolanas with high percentages of silica content as well as quarry dust such as fly ash, ground granulated blast furnace slag, rice husk ash, and silica fume recorded an increase in strength and durability properties. Referring to research done by Ravikumar et al (2013), pozzolanas show increased durability properties with the content and type of silica, meanwhile, the type, amount, and fineness of the pozzolanas are the factors that affect the strength and durability of the cement composites. These pozzolanas chemically react with the calcium hydroxide that is released by the hydration of Portland cement to form compounds possessing cementitious properties to be more economical, reduce permeability, and increase strength and durability (Ravikumar et al., 2013).

Among these pozzolanas, quarry dust was chosen because of its availability and detrimental effect on the environment, including human beings and plants. Briefly, quarry dust has the potential to improve the strength and durability of cementitious structures, which is attributed to better interlocking and high silica content. The investigation of quarry dust and marble sludge powder as substitutes for natural sand in concrete revealed that the compressive strength, split tensile strength, and durability was improved and the resistance to sulfate attack was enhanced greatly (Hameed and Sekar, 2009). The fine particles of quarry dust play an important role in filling large pores and internal gaps in the slurry to generate a compact microstructure, which is beneficial for the increase of compressive strength (Ying et al., 2013). Furthermore, Mangurui et al (2013) added the use of quarry dust as fine aggregate tends to improve certain engineering properties such as compressive strength, durability, and workability in the cementitious product. At this point, the research aims to investigate the capability and resistivity of quarry dust in cement composites against sulfate attack at predetermined periods.

3.0 Experimental Setup

The specimens of cement composites were evaluated in the laboratory for Durability Test (Length Change Due to Sulfate Attack). In this test, the optimum proportions of cement composites were depicted from the previous proportioning study and selected to observe the length change and surface deterioration when exposed to sulfate solution. According to the obtained findings, the percentage of 12.5 wt.% of quarry dust showed good results in physical and mechanical properties, meanwhile, the quarry dust's consumption at 17.5 wt.% showed the lowest values. In this case, the paper compared the durability properties of cement composites when subjected to sulfate attack with the addition of quarry dust at 0 wt.% as a reference sample, 12.5 wt.%, and 17.5 wt.% as shown in Table 1.

Table 1: Proportions of quarry dust in cement composites in durability study

Sample (Quarry dust: Sand)	Quarry dust (%)	Cement: Sand: Quarry dust (wt.%)	Water cement ratio
0.00: 1.00	0.00	1:1.000:0.000	0.45
12.5: 87.5	12.5	1:0.875:0.125	0.45
17.5: 82.5	17.5	1:0.825:0.175	0.45

The procedures of the sample's preparation and testing were operated by following the ASTM C1012/C1012M-13 (Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution). This test method covers the determination of the length change of mortar bars immersed in a sulfate solution. Mortar bars are casts as described in Standard Test Method for Compressive Strength of Hydraulic Cement Mortar

(ASTM C109/C109M-11b) and are cured until attaining a compressive strength of 20 ± 1.0 MPa as measured using cubes made from the same mixture before immersed. As guided in the standard, the samples of cement composites were cast in cubes of 50 mm x 50 mm x 50 mm, and prims of 25 mm x 25 mm x 285 mm and were allowed to be set down for 24 hours before immersing into the solution of calcium hydroxide, $Ca(OH)_2$. This solution can be used to neutralize acidic solutions and is typically used to test the presence of carbon dioxide because of a precipitate of calcium carbonate. After the saturated calcium hydroxide was ready in terms of pH value and appeared clear and colorless, the hardened samples of cement composites were immersed for 7 and 28 days. Upon reaching the age of 7 and 28 days, the immersed samples were taken out from saturated calcium hydroxide and were compressed under vertical load using a universal testing machine (UTM).

The next process is the sulfate solution was prepared by using 50 g/L of anhydrous sodium sulfate (Na_2SO_4) and diluted with distilled water to transform into the salty solution in a controlled pH value. The samples of cement composites were immediately immersed in the sodium sulfate solution for 1,2,3,4,8,13 and 15 weeks. During the immersion, the samples of cement composite were treated according to the guided standard. The container of the cement composites was covered and sealed to prevent evaporation from the inside, or dilution with water from the outside. The sodium sulfate solution used for the immersion test is renewed every 4 weeks to reduce the increase in pH due to the leaching of OH-ions from the samples of cement composites. This procedure is to avoid the solution reaching the pH of saturated $Ca(OH)_2$ solution and to compensate for the loss of the concentration of the sulfate solution due to the process of degradation (Nasser and Meriam, 2013). The samples of cement composites were continuously immersed in the sulfate solution and the observations have been done for length change at a certain period of immersion and visual examination of any deterioration.

4.0 Results and discussion

The samples of cement composites were observed at every predetermined period to measure the length change regarding the sulfate attack. At 1, 2, 3, 4, 8, 13, and 15 weeks after the cement composites are placed in the sulfate solution, length changes are measured by using the length comparator. According to the results, the length of cement composites before and after immersion in sulfate solution did not show an alteration from the beginning to the last week of immersion.

A visual examination was carried out at every period of immersion to evaluate the visible signs of degradation due to material damage and spalling on surfaces of cement composites. According to the investigation, no surface sign deterioration was detected on the samples of cement composites at 1, 2, 3, and 4 weeks respectively. No sign of spalling was observed and no layer of salt deposition on the surface of the cement composites. However, on weeks 8, 13, and 15, there was a little deterioration on the surfaces of the cement composites.

According to Figure 1, the samples without the addition of quarry dust (0 wt.%) showed the appearance of slat crystallization or efflorescence on the surface of the cement composites. This situation happened when there has no addition of quarry dust in the samples, which tends to block the gap between the mixture particles and reduce the path for soluble salts to migrate through the surface of the cement composites. The justification was parallel with the statement by Michael (1986), salt crystallization occurred in the combination of three conditions such as water-soluble salts, sufficient moisture in the structure to render the salt into soluble solution, and a path to migrate through the surface which can cause efflorescence. This process was described as a physical attack on cement composites and did not involve any chemical interaction between the sulfate ions and the hydration of cement composites. However, if untreated, the trapped salt can be crystallized and its expansion tends to form cracks and spall the structures or lead to masonry problems (Patrick, 2007). Besides that, the findings revealed the utilization of ordinary Portland cement that is high in tricalcium aluminate (C_3A) compound and there has no improving resistance such as used the addition of pozzolanas could not resist the sulfate attack, as stated by Murdock et al (1991). In addition to this, Eglinton (1998) and Lota (1995) stated that the principal reason for the mortar resistance concerning sulfates is due to the low quantity of calcium aluminate hydrates (C_3A).

Figure 1: Cement composites without the addition of quarry dust

Next, Figure 2 showed the samples of cement composites with the addition of quarry dust at 12.5 wt. %. Regarding Figure 2, there have no obvious signs such as slat crystallization and major deteriorations were detected on the surface or edges of the cement composites, almost confirmed by the findings revealed by Nasser and Meriam (2013) until 90 days of immersion in a sodium sulfate solution. According to the previous result from proportioning study, the strength properties of the cement composites such as compressive and tensile strength showed the highest value amongst the rest, and at the same time lowest in water absorption and moisture content. The consumption of quarry dust in the cement composites improved the durability and strength properties due to the excellent resistance related to the silica and filling action. The fine particles of quarry dust increase the resistance of cement composites against sulfate attack by decreasing the porosity and permeability factor. The excellent resistance is related to the filling action of fine particle size, and the pore refinement process occurring due to the conversion of portlandite into secondary C-S-H gel through a strong pozzolanic reaction (Lee et al., 2005).

Figure 2: Cement composites with the addition of 12.5 wt. % quarry dust

However, the samples of cement composites with 17.5 wt. % of quarry dust in Figure 3 showed obvious degradation at the edges of the cement composites but did not show any sign of efflorescence. This situation happens as the previous explanation of the pozzolanic effect with the addition of 12.5 wt.% of quarry dust in cement composites. The cement composites displayed degradation starting at the surface and corners, and progressively enters into cement composites by scaling and spalling, whereby finally reduces into friable mass (Shetty, 1986). The damages answered the findings of the lowest compressive strength obtained during the proportioning study. Furthermore, the other factors influencing the deterioration of cement composites are regarded as the high value of water absorption and moisture content in previous findings. The high percentages of quarry dust might be one of the factors that contribute to the alkali-silica reaction (ASR) in cement composites. ASR occurred when three conditions as well as reactive forms of silica in quarry dust, high alkalinity in pore solution, and sufficient moisture (Portland Cement Association, 2007) exist in cement composites. The combination of alkali-silica gel and moisture triggered the pressure and create the tendency to induce the deterioration of scaling and durability properties of the cement composites.

Figure 3: Cement composites with the addition of 17.5 wt. % quarry dust

5.0 Conclusion

According to the findings, there has no length change occurred in the specimens of cement composites from starting to the end week of the immersion period in the sodium sulfate solution. Nevertheless, the specimens showed surface deterioration after 8 to 15 weeks immersed in the solution of sodium sulfate. The salt crystallization occurred at the surface of the specimens without the addition of quarry dust compared to the specimens mixed with the addition of quarry dust respectively. In other words, the strength and durability properties of the cement composites influenced the capability to resist the sulfate attack. Ordinary Portland cement can be used in marine structures by substituting quarry dust as a partial replacement of sand to reduce the high purchases of sulfate-resisting cement.

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