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Properties, durability and cost efficiency of cement and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus

Abstract

The unexpected closure of the mine processing area of Lefke-Xeros generated the largest environmental disaster in the recent history of Northern Cyprus. The mining area, formed the biggest industry on the island in 1950s, was unpredictably closed and left all mine tailings and equipment behind without any preservation towards the environmental remediation nor sustainable rehabilitation for the locality. Substantial increase in the cost of energy supply, determination to decrease CO₂ emissions and to reduce the consumption of natural materials on the other hand, are the major challenges in construction practice. The paper is investigating the consequences of dewatering by means of recycling copper mine tailings in mortars both for the sustainable development of construction materials and for the socio-economic recovery of Lefke-Xeros area of Cyprus. The degree of dewatering as a consequence of the substrate/mortar interaction on the mechanical and physical properties of cement and lime mortars containing copper tailings are reported in the paper. Physical measurements provided an insight into the actual effect of dewatering on the resistance of freezing and thawing action of mortars containing copper tailings. The use of copper tailings and therefore the degree of dewatering have shown to play a substantial role in the decrease in thermal conductivity and increase in cost efficiency of these mortars in construction practice. The results reported in this paper significantly contribute in the sustainable development of construction materials through the use of mine tailings to support environmental sustainability and socio-economic development of Lefke-Xeros area of Cyprus.

Keywords

Copper mine tailings; dewatering; mechanical and physical properties; reusing; cost efficiency

Word Count: 7625

Introduction

Lefke town, located in the north-western part of the island and approximately 74 km west of the capital, Nicosia, has always been one of the most significant settlements in Northern Cyprus because of its rich mineral deposits [1]. The unexpected closure of the mine processing area of Lefke-Xeros in 1974, previously owned by Cyprus Mining Corporation (CMC), generated the largest environmental disaster in the recent history of Northern Cyprus. CMC was authoritatively recognised and activated three mining sites Skouriotissa, Mavrovouni and Apliki near the town of Lefke in 1916 where the mine ores from these sites were processed in the treatment plants located near the coast of Gemikonagi. Copper and gold were the main produced minerals. The mining area, formed the biggest industry on the island in 1950s, was unpredictably closed and left all mine tailings and equipment behind without any preservation towards the environmental remediation nor sustainable rehabilitation for the locality. Following the mine site was abandoned, Lefke, once had the largest industry in the region, was left with toxic wastes that contaminated both the lands and underground water resources [2, 3]. The environmental and agricultural sustainability, ecological footprint as well as the socio-economic development of the region, therefore is adversely influenced by the sudden closure of Lefke mining area due to the tailings that are still out in the open and are remained to contaminate the nearby sea and groundwater along with the immediate environment [4].

Copper and copper alloy products are frequently used in construction, transportation, telecommunication and electrical and electronical practices due to their high conductivity and durability [5]. According to the International Copper Study Group [6], the world refined copper usage reached over 24 Mt by the end of 2019. Lower grades of ores, processed to meet the increasing demand, however produced greater amounts of wastes. Gordon [7] projected that 128 tons of solid tailings are generated during the production of 1 ton of copper. The increase in the demand of using copper and copper-slag products, a by-product material arisen from the copper manufacturing practices [8, 9, 10], generated nearly 40 million ton of the waste-slag per year around the world [11].

The detrimental impacts on the environmental sustainability, economic growth, pollution and associated health hazards as a result of the poor governance of mine tailings, well documented in the literature, are the globally growing concerns of the entire planet. Generation of acids through the oxidation, high concentrations of metal and acid, as well as high concentrations of zinc and nickel are the main causes of the soil contamination, sea and ground water pollution and acid mine drainage [12, 13, 14, 15, 16]. Construction industry, on the other hand, is dramatically contributing to global energy consumption and CO₂ emissions [4, 17]. Cement production for instance is accounting for ~12-15% to the total industrial energy consumption and 5% of anthropogenic CO₂ emission [18, 19]. More importantly, the devastating adverse effects of the CO₂ emissions on the climate change is reported by Pierrehumbert [20]. The significances of bringing the net carbon dioxide emissions to zero by the world economy in order to

cease the global warming are emphasised as the cumulative emissions over the prolonged period of times govern the actual damage encountered to the climate. It is unfortunate that the current annual emission growth rates are twice as large as in 1990s [21]. This indicates that unless we dramatically reduce the emissions, the temperature rise approaches or exceeds 2°C guardrail [22, 23] according to the Article 2 of the United Nations Framework Convention on Climate Change [23]. It is reported by the World Bank that warming of 2 degrees Celsius would have been dreadful enough and 4 degrees Celsius of global warming would be “cataclysmic.” Substantial increase in the cost of energy supply, determination to decrease CO₂ emissions and to reduce the consumption of natural materials and associated global warming are the major challenges in construction practice and hence, investigation of the possible incorporation of the mine tailings in the production of construction materials is an alarming responsibility of the researchers to support the sustainable development of the construction materials and to maintain environmental sustainability and the socio-economic recovery of the Lefke- Xeros area of Cyprus.

Although limited, published studies in the literature demonstrated the successful use of mine tailings in construction practice. For instance, the productive use of phosphate mine waste as an aggregate replacement in concrete was reported in 1993 [24]. The effective use of iron and gold ores, generated in the mine areas of Western Australia, for the highway and railway embankments was then reported in 2013 [25]. Fernando et al. [26] also reported the use of tungsten mine waste mud for the enhanced acid and abrasion resistance of concrete. Later in 2019, Ince [4] also reported the compatible utilisation of gold mine tailings, attained from Lefke-Xeros area of Cyprus, in cement mortars. There are also several published studies in the literature concerning the use of copper tailings in cement based materials. For instance, the results shown in Moura et al. [27] exhibited the compatibility of the use of copper slag as a partial replacement in producing concrete. The results showed an increase in compressive strength and a subsequent decrease in the absorption and carbonation depth and hence demonstrated a considerable improvement of durability of concrete incorporated copper slag. The results reported in Thomas et al. [28], Tamil et al. [29] and Patil [30] are in good correlation with Moura et al. [27]. Similar results also reported in Gupta et al. [31] stated that the use of copper tailings enhanced both the mechanical and physical properties and provided significant improvement in durability of concrete. Improved durability of concrete incorporating mine tailings was also reported in Fernando and Said [32] and that enhanced resistance to abrasion and of acid attack of concrete with tailings were attributed to the low water absorption properties of these mine tailings. More importantly, the successful incorporation of copper tailings attained from the Lefke-Xeros area on the corrosion performance of concrete was reported in Onuaguluchi and Eren [5]. The study has shown that the copper tailing significantly improved the corrosion resistance of concrete and suggested an alternative mitigation measure to develop the environmental sustainability of the locality.

Incorporation of copper tailings on lime mortars, nevertheless, have not been previously reported in the literature however there are few studies that used lime as an additive in making paste and mortar specimens containing copper slag. For instance, Tixier et al. [33] studied the paste samples made using copper slag and hydrated lime to investigate the pozzolanic character of the slag. X-ray diffraction conducted on specimens containing 95% of copper slag and 5% of hydrated lime showed high pozzolanic index. Later in 2002, Al-Jabri et al. [34] studied the properties of mortars prepared using 3.5-13.5% of copper slag, 85-95% of cement by-pass dust and 1.5% of lime. It was reported in the study that the use of cement by-pass dust and copper slag was effective in increasing the compressive strength of mortars whereas the use of lime did not contribute in the development of mechanical properties. The studies reported on the utilisation of copper slag in mortars and concrete also provided significant insights into this area. For instance, Song et al. [35] reported the prolong induction period and reduced early heat of hydration as well as heat of hydration rate attainment due to the dilution of cement clinker with 20% copper slag. Sharma and Khan [36] reported an increase in the splitting tensile strength of concrete with the increase in the substitution level of copper slag. Incorporation of metakaolin reported to further contribute in increasing the splitting tensile strength of these mixes. Pull-off adhesion test conducted on the concrete specimens containing copper slag showed that bond strength of concrete incorporated with copper slag up to 60% was identical to the control specimen whereas the noticeably reduced bond strength was attained at high percentages of copper slag [37]. High electromagnetic wave absorption and compressive strength of copper slag-filled cement mortars were also reported to be attained at 50% replacement level [38]. Copper tailing incorporation reported to decrease the permeability of concrete and therefore enhanced water and chloride ion permeability as well as higher resistance to sulphate attack was attained [39].

Abovementioned studies significantly contributed insights into the use of mine tailings in construction practice however, the influence of the incorporation of these tailings on dewatering freshly mixed mortars as a consequence of the substrate-mortar interaction in masonry construction has not been addressed in the literature. The crucial factors that affect the water retaining ability of lime and cement mortars, previously reported in Ince et al. [40], demonstrated significant variations in the desorptivity characteristics of lime and cement mortars. The substantial differences in the water retaining ability further has shown to influence the water transport kinetics of these mortars particularly when they are in contact with an absorbent substrate [41]. Experimentally validated equation, derived based on the Sharp front theory, showed that dewatering critically depends on the hydraulicity of the freshly mixed mortars and could results in 40-60% loss of mix water. Predictions based on the Sharp front theory are also re-validated using impedance spectroscopy in Ball et al. [42]. Effects of dewatering and important consequences of this occurrence in construction practice was first reported in El-Turki et al. [43]. Influence of the supplementary cementing materials on the water transport kinetics of freshly mixed mortars to attain better optimisation in mortar/substrate was reported in Ince et al. [44]. The study has

shown that utilisation of the supplementary cementing materials manipulates the parameters of water transport kinetics of lime and cement mortars and further support the wet mortar/substrate optimisation to be developed in masonry construction. The ability to manipulate the water transport kinetics of mortars incorporating supplementary cementing materials and hence degree of dewatering has shown to have important consequences in the hardened state properties of these materials in Ince et al. [45]. Significant improvements on the mechanical properties of both lime and cement mortars incorporating supplementary cementing materials were also supported with the microstructural analysis in the study. Interrelated studies in the literature emphasising the influence of the use of pozzolanic materials and hence the effect of dewatering both on the fresh and hardened state properties of lime and cement mortars were also addressed in Ince et al. [46] and later in Derogar [47]. Further studies by Ince et al. [48] and Ince [49] provided detailed insights into the water retaining mechanism of hydrated lime mortars and demonstrated that the water retaining ability is not due to particle size of raw material alone, and that the simple ionic solution as mix water has significant contributions on the water transport kinetics and on the associated properties at the hardened state.

The paper therefore is investigating the consequences of dewatering by means of recycling copper mine tailings in mortars both for the sustainable development of construction materials and for the socio-economic recovery of Lefke-Xeros area of Cyprus. Following a detailed characterization study conducted on the copper tailings obtained from the Lefke-Xeros area of Cyprus, the degree of dewatering as a consequence of the substrate/mortar interaction of cement and lime mortars containing copper tailings is measured. The paper has shown that the effect of dewatering and therefore the resulting water:binder ratio of cement and lime mortars containing copper tailings have important consequences both on the fresh and hardened state of these materials. The utilisation of copper tailings, shown to manipulate the water transport kinetics and hence the degree of dewatering freshly mixed mortars, on the compressive strength, flexural strength, split tensile strength and shear bond strength of cement and lime mortars are examined in the paper. Water penetration depth and porosity experiments performed prior to the measurements of freezing and thawing resistance of mortars containing copper tailings provided insights into actual dewatering incidences and its influences on the durability of such mortars. The use of copper tailings and therefore the reduced degree of dewatering have shown to play a substantial role in the decrease in thermal conductivity and improved thermal insulation properties of these materials in construction practice. Cost efficiency of mortars containing copper tailings therefore the influence of dewatering on the cost efficiency mortars are also reported in the paper. The results reported in this paper significantly contributes in creating awareness of the need to contribute in sustainable development of construction materials through the use of mine tailings to support environmental sustainability and socio-economic development of Lefke-Xeros area of Cyprus.

2. Materials and Mix Design

Hydrated lime, Portland cement, standard sand and copper tailings formed the main constituent materials for mortars. CL80, the hydrated lime binder, and CEM I 32.5 N, the cement binder, conform to TS EN 459-1 [50] and ASTM C150/C150M-16 [51] respectively. The fine aggregates used in the mortar production conforms TS EN 196-1 [52]. Mix design calculations are conducted based on the carefully determined bulk densities of the raw materials and the fixed mix volume proportions of 0.6:1:2 of water:lime:sand and 0.52:1:2 of water:cement:sand for lime and cement mortars respectively. Copper tailings, used as a binder replacement to support the environment sustainability as well as to remediate the socio-economic development of Lefke-Xeros area of Northern Cyprus, are shown in Figure 1. Copper mineralization has taken place following the early phase of pyrite deposition at Lefke-Xeros area which is dominated by Fe-Cu mineralization. Copper tailings are used as a partial replacement to lime and cement binder in this study. The map of the study area, designating the tailings ponds, is also shown in Figure 2. The mix constituents of lime and cement mortars examined in the paper are summarised in Table 1. Replacement levels of copper tailings were 5%, 10%, 15% and 20%. Following the cast work, cement mortar specimens were confined with a moist duster for 24 hours and then were de-moulded and stored in the curing tank at a temperature of $24 \pm 2.0^\circ\text{C}$ until the specified test dates. Lime mortars were demoulded 3 days after they were cast and stored in the ambient conditions in the laboratory until the specified test dates. Specimens subjected to the freezing and thawing action were placed in the freezing and thawing cabinet for a specified period of time.

3. Experimental Procedure

3.1 Characterization

Characterization study, conducted at Central Laboratory of Middle East Technical University, comprised the chemical composition using X-ray fluorescence, microstructural analysis using scanning electron microscope, particle size distribution using Mastersizer and basic physical properties of the raw materials examined in the paper. Rigaku ZSX Primus II is used to conduct the chemical composition of the powdered specimens of lime, cement and copper tailings. Quanta 400F Field Emission, high resolution scanning electron microscope with a resolution of 1.2 nm is also utilised to investigate the microstructural properties of copper tailings used as a partial replacement level in lime and cement mortars in this study. A thin layer of gold platinum alloy was sputtered onto the surface of the copper tailings to reduce the charging under the electron beam. Particle size distribution of the raw materials is determined using the Malvern Mastersizer 2000 based on the Mie scattering measuring principles with a grain size range from 0.02 to 2000 microns.

3.2 Water transport kinetics

Sorptivity, transfer sorptivity and the water loss of freshly mixed mortars in contact with absorbent substrates constitute the water transport kinetics of mortars containing copper tailings examined in this paper. Sorptivity, the ability of a dry absorbent material to absorb water by capillarity, is measured

following the procedure given in Ince et al. [41]. Clay bricks are dried in the oven at 105°C over the night and then are placed in a shallow layer of water. Specimens were removed from the water and weighed at time intervals. The sorptivity of clay bricks were determined from the gradient of a plot of the cumulative absorbed volume of water per unit area of absorbing surface of the bricks versus the square root of time were then plotted. The transfer sorptivity, A , is a function of both the desorptivity of the freshly mixed mortars and the sorptivity of the absorbent material. Transfer sorptivity defines the ability of a dry substrate to absorb water from a wet mix [41]. Following clay bricks are dried in the oven at 105°C, the specimens were placed in contact with a shallow layer of freshly mixed mortars. Similar to the sorptivity determinations, the transfer sorptivity is defined as the gradient of a plot of the cumulative absorbed volume of water per unit area of clay bricks in contact with the wet mix versus the square root of time.

3.3 Fresh state properties

Consistency and setting time of mortars containing copper tailings are measured following the standard procedures provided in ASTM C230/C230M-14 [53] and ASTM C807-18 [54] respectively. Consistence of wet mixes is measured using the flow table and setting time of mortars is measured using the Vicat apparatus.

3.4 Mechanical and physical properties

Flexural and compressive strength of cement and lime mortars containing copper tailings are conducted following the standard procedure given in ASTM C348-20 [55] and ASTM C349-18 [56] respectively. Split tensile strength of mortars are examined using the standard procedure given in ASTM C496 [57] and the shear bond strength of mortars in conjunction with the clay masonry unit is examined following the procedure given in Singh and Munjal [58].

3.5 Durability

Physical measures such as water penetration depth and porosity performed following the standard procedures given in BS EN 12390-8 [59] and ASTM D4404-10 [60] respectively provided an insight into the associated durability characteristics of the resistance to freezing and thawing [61] and the thermal conductivity [62] of mortars examined in the paper.

3.6 Cost efficiency

Cost efficiency factor (CEF) of mortars containing copper tailings, calculated based on Equation (1), is the ratio of the compressive strength of mortars to the total material cost per m³ [63, 64]. The local prices of constituents at the time of the study in North Cyprus are utilised to conduct the cost estimates and are stated in dollars in this paper. \$0.14 per kg of hydrated lime, \$0.12 per kg of cement and \$14.86 per m³

of fine aggregates are used to define the cost efficiency factor. 0.03\$ of the total cost of grinding the copper tailings per kg was also taken into consideration in cost efficiency factor.

$$CEF = \frac{F_c}{C} \times 100 \quad (1)$$

Where F_c is the average compressive strength of mortars and C is the cost of materials per m^3 of mix constituents.

4. Results and Discussions

4.1 Characterisation

Chemical composition of X-ray fluorescence summarized in Table 2 showed typical distributions in kind and in magnitude for hydrated lime and cement binder. Copper tailings, on the other hand, have shown to be rich in Fe_2O_3 , SiO_2 and CaO and in a good agreement with the distributions reported by Alp et al. [65], Gorai et al. [66] and Onuaguluchi and Eren [5]. Particle size distribution of hydrated lime, cement, copper tailings and sand is shown in Figure 3. Copper tailings demonstrated finer particle size distribution than cement and coarser distributions than that of hydrated lime binders. Scanning electron microscope image of the copper tailings, shown in Figure 4, demonstrated a typical of square grid pattern of the copper tailings and validated the particle size distributions shown in Figure 3. Heavy metal content and physical properties of copper tailings are summarised in Table 3. Although there are some studies in the literature indicating delayed hydration and a consequent increase in the setting time of these mortars, the heavy metal contents of copper tailings, given in Table 3, were considerably low and therefore the aforementioned incidences were not distinguished with mortars containing copper tailings examined in this paper [67, 68]. Physical properties summarised in Table 3 re-validated the high fineness and high water absorption characteristics of copper tailings. Characterisation study conducted in the paper enlighten the compatibility of utilising the copper tailings in mortar making. The study reported by Kundu et al. [69] also demonstrated the compatibility of the copper tailings in concrete when used as a partial substitute for cement hence further suggested the economic and sustainable use of these wastes in construction materials. Shi et al [70] also demonstrated that copper slag is not a hazardous waste based on the various criteria such as United States Environmental Protection Agency and therefore reusing and recycling operations can be encouraged in construction practice and other areas of industry.

4.2 Transfer Sorptivity and Water Loss

Transfer sorptivity and water loss of freshly mixed mortars containing copper tailings are investigated in this section. Equivalent water suction characteristics is achieved using constant sorptivity of ~ 2.1 mm/min² clay bricks throughout the transfer sorptivity experiments. Water loss is calculated based on the recorded initial water content of the mix as well as the water absorption of the dry brick in contact with the freshly mixed mortars.

Transfer sorptivity of cement and lime mortars containing copper tailings are shown in Figure 5. Water loss of these mortars when they are in contact with the dry brick substrates at the freshly mixed state is also plotted in the secondary axis in Figure 5. The results shown in Figure 5 demonstrated that transfer sorptivity of very water releasing cement mortars is decreasing systematically with the increase in the replacement level of copper tailings. Transfer sorptivity is a function of the water retaining characteristics of freshly mixed mortars and the sorptivity of the dry substrate. Since the sorptivity of the substrate is kept constant in these experiments, increase in the water retaining characteristics and consequently the decrease in the water releasing ability achieved with the increase replacement level of copper tailings are mainly responsible from the reduction in the transfer sorptivity of cement mortars. Finer particle size of copper, compared to that of cement, resulted in a more consolidated and denser mixtures to be obtained and made the water transfer from these mixtures into the dry substrates more difficult. The increase in the replacement level of copper tailings therefore resulted in a systematic decrease in the associated water loss and that is in a good agreement with the decrease in transfer sorptivity of cement mortars. It is also shown in Figure 5 that very water retaining lime mortars are becoming more water releasing with the increase replacement level of copper tailings. Transfer sorptivity of lime mortars are increasing with the increase replacement level of copper tailings and that the associated increase in the water loss of these mixtures are in a good agreement with this occurrence. In this case, the binder is partially replaced with a coarser particle size of tailings that resulted in a less consolidated and more porous mixtures and facilitated easier water transfer to be performed from the freshly mixed mortars into the dry substrates. The use of copper tailings as a partial replacement have shown to significantly influence the transfer sorptivity as well as the water loss and hence the water:binder ratio of the resulting cement and lime mortars. The results are in a good agreement with previously published work [41, 45, 46, 47]. The influence of the extent of transfer sorptivity and hence the degree of dewatering along with the changes in water:binder ratio on the mechanical properties and durability characteristics of these mortars are reported in the subsequent sections.

4.3 Consistence

The consistence of cement and lime mortars contained increasing replacement level of copper tailings are reported in this section. The influence of dewatering on the consistence of these mortars are also investigated in this part of the paper. The consistence of cement and lime mortars containing copper tailings are shown in Figures 6a and b respectively.

It is shown in Figure 6a that increase in the replacement level of copper tailings resulted in a decrease in the consistence of cement mortars. The decrease in the consistence is attributed to the finer particle size of copper tailings that enabled denser mixtures to be generated. The dewatering, on the other hand, resulted in a reduced water:binder ratio of cement mixtures and further contributed to the decrease in the consistence of these mortars. It must however be noted that the cement mortars (control specimen)

with the highest water releasing characteristics resulted in a greatest loss of water during dewatering and hence performed the greatest difference in consistence between the dewatered and non-dewatered cement mortars. Increase in the copper tailings resulted a more water retaining mortars to be generated and hence further decreased the water loss during dewatering and consequently reduced the difference in consistence between the dewatered and non-dewatered cement mortars.

It is shown in Figure 6b that increase in the copper tailings resulted in an increase in the consistence of lime mortars. This is attributed to the decrease in the surface area of solids due to the coarser particle size of copper tailings compared to that of lime. The dewatering lime mortars contained copper tailings resulted in a decrease in the consistence of these mortars as a resulted of the reduced water:lime ratios attained following dewatering. Lime mortars are very water retaining and hence dewatering these mortars did not significantly changed the consistence due to the inconsiderable amount of water loss attained during dewatering. The increase in the copper tailings resulted in a more water releasing mortars to be generated and hence greater water losses are attained during dewatering. Increase in the water loss experienced following dewatering generated greater differences in consistency between the dewatered and non-dewatered lime mortars. It must be noted however that consistence values reported for cement and lime mortars containing copper tailings are in the range of 120mm to 137mm and are adequate to form a flowable-plastic mixtures.

4.4 Setting Time

Influence of the use of copper tailing and its associated effect of dewatering on the setting time of cement and lime mortars are shown in Figures 7a and b respectively. It is shown in Figure 7a that increase in the copper tailings resulted in a slight decrease in the setting time of cement mortars. This is attributed to the finer particle size of copper tailings that enabled consolidated cement mixtures to be generated and hence accelerated hydration. The dewatering resulted in a reduced water:binder ratios of cement mixtures and further accelerated the hydration reactions and therefore generated a considerable decrease in the setting time of these mortars. The control specimen, cement mortars, are very water releasing and hence experienced the greatest water loss during dewatering and exhibited the greatest difference in setting time between the dewatered and non-dewatered cement mortars. Increase in the replacement level of copper tailings resulted in a decrease in the water releasing ability of cement mortars and consequently resulted in a decrease in the water loss of these mortars along with the reduced differences in setting times between the dewatered and non-dewatered cement mortars. The results reported in this paper are in good agreement with Gopalakrishnan and Nithiyantham [71] that reports the development of the denser structure which helps accelerating the setting time of mixtures containing copper slag.

It is shown in Figure 7b that increase in the copper tailings resulted in a considerable decrease in the setting time of lime mortars. This is attributed to the reduced lime content of the mixtures that enabled

faster settings to take place. The control lime mortars are very water retaining and hence experienced the least water loss during dewatering and exhibited the smallest difference in setting time between the dewatered and non-dewatered lime mortars. Increase in the replacement level of copper tailings resulted in a decrease in the water retaining ability of lime mortars and consequently resulted in an increase in the water loss of these mortars along with the increased differences in setting times between the dewatered and non-dewatered lime mortars.

4.5 Compressive Strength

The influence of the increasing replacement level of copper tailings and consequently the effect of dewatering on the compressive strength of cement and lime mortars are shown in Figures 8a and b respectively. It is shown in Figure 8a that increase in the replacement level of copper tailings resulted in a slight increase in the compressive strength of non-dewatered cement mortars. Nearly 28% of increase attained in the compressive strength of cement mortars are mainly attributed to the finer particle size of the copper tailings that enabled denser and less porous mortars to be developed. The increase attained in compressive strength of cement mortars containing copper tailings are in good correlation with Onuaguluchi and Eren [72] and Moura et al. [23].

It is previously discussed in the paper that the increasing the replacement level of copper tailings transformed the very water releasing cement mortars to be more water retaining. Control specimen, for instance, had the greatest water loss during dewatering as this is the most water releasing mortars. The increase in the replacement level of copper tailings resulted in a systematic decrease in the water loss during dewatering due to the formation of more water retaining cement mortars. The greatest water loss experienced by the most water releasing control specimen indicated a substantial reduction in water:cement ratio during dewatering. The significant decrease in the water:cement ratio resulted in the substantial increase in the compressive strength of cement mortars. As the replacement level of copper tailings increased, the mortars systematically became more water retaining and hence the water loss during dewatering also systematically decreased. The influence of the reduced water loss during dewatering was more eminent than the increasing replacement level of copper tailings on the compressive strength of cement mortars. It is shown in Figure 8a that dewatered cement mortars contained increasing replacement level of copper tailings resulted in a systematic decrease in the compressive strength of cement mortars due to the reduced water loss attained during dewatering. Incorporation of 20% of copper tailings resulted in approximately 15% of decrease in the compressive strength of cement mortars.

It is shown in Figure 8b that increase in the copper tailings resulted in an increase in the compressive strength of non-dewatered lime mortars. Increase in the replacement level of copper tailings transformed the very water retaining mixtures into more water releasing lime mortars. It is also shown in Figure 8b

that increase in the copper tailings resulted in a systematic increase in the water loss of lime mortars during dewatering as a result of the increased water releasing ability attain in these mortars. The increase in the replacement level of copper tailings along with the systematic increase in the water loss during dewatering and hence the reduced water:lime ratios attain played a great role in increasing the compressive strength of lime mortars containing copper tailings. Incorporation of copper tailings resulted in 87% and 136% increase in the compressive strength of nondewatered and dewatered lime mortars respectively. It must be noted however that the greatest water loss experienced with the highest replacement level of copper tailings (20%) resulted in the greatest difference in compressive strength between the dewatered and non-dewatered lime mortars. As the water loss experienced during dewatering decreased with the decrease in the replacement level of copper tailings, the difference in the compressive strength of dewatered and non-dewatered lime mortars is curtailed.

4.6 Flexural Strength and Split Tensile Strength

Flexural strength and split tensile strength of dewatered cement and lime mortars containing copper tailings are shown in Figure 9. Due to the differences in scale, flexural strength of lime mortars is plotted on the secondary axis in Figure 9. It is shown in Figure 9 that increase in the replacement level of copper tailings resulted in a systematic decrease in the flexural strength and the split tensile strength of dewatered cement mortars. Although copper tailings have shown to increase the compressive strength of non-dewatered cement mortars, the predominate cause for this observation is mainly attributed to the development of more water retaining cement mortars as a result of the increased replacement level of copper tailings. The increased water retentivity resulted in a reduced water loss and hence smaller decreases in water:cement ratios of mortars containing increased replacement level of copper tailings. This occurrences resulted in a systematic decrease in both the flexural and split tensile strength of mortars containing increased replacement level of copper tailing.

It is also shown in Figure 9 that increase in the replacement level of copper tailings resulted in an increase in both the flexural and split tensile strength of dewatered lime mortars. It is previously shown in the paper that replacing lime with copper tailings had an increasing effect on compressive strength. It must also be noted that high water retaining characteristics of lime mortars are transforming into more water releasing and therefore are dewatered to a greater degree when in contact with the dry substrate. The greater loss of water and hence reduced water:lime ratios during dewatering further contributed in the increase in flexural and split tensile strength of lime mortars.

4.7 Shear Bond Strength

Shear bond strength of dewatered cement and lime mortars containing copper tailings are shown in Figure 10. The increase in the replacement level of copper tailings resulted in an accelerating decrease in the shear bond strength of dewatered cement mortars. The increase in the replacement level of copper

tailings generated less water transfer from the freshly mixed mortars to dry substrate and therefore more water retained mortars developed using copper tailings resulted in a slight decrease in the shear bond strength of cement mortars. The flexural strength of dewatered cement mortars containing copper tailings, shown in the secondary axis in Figure 10 is in a good correlation with the shear bond strength at all replacement levels of copper tailings examined in the paper. The increase in the replacement level of copper tailings on the other hand resulted in an increase in the shear bond strength of dewatered lime mortars. This is mainly attributed to the formation of more water releasing lime mortars generated using increased replacement level of copper tailings. This transformation of lime mortars enabled greater amount of water transfer to be performed from the freshly mixed mortars into dry substrates and hence resulted in a reduced water:binder ratio as well as enabled stronger bonds to be developed at the fresh state of lime mortars. The flexural strength of dewatered lime mortars containing copper tailings, shown in the secondary axis in Figure 10 is also in a good correlation with the shear bond strength of lime mortars at all replacement levels of copper tailings.

4.8 Water Penetration Depth and Porosity

The influence of the copper tailings on the water penetration depth of dewatered and non-dewatered mortars as well as the correlation with the porosity of dewatered mortars are investigated in this section. It is shown in Figure 11a that increase in the replacement level of copper tailings resulted in a decrease in the water penetration depth of non-dewatered cement mortars as a consequence of the increase in the particle size of fine materials. These physical measures are in good correlation with the published data in the literature [23, 71, 73]. Increase in the replacement level of copper tailings enabled more water retaining cement mortars to be generated and hence increased water:binder ratios of mortars to be attained that resulted in a systematic decrease in water penetration depth of dewatered cement mortars. It is also shown in Figure 11a that increase in the replacement level of copper tailings resulted in a systematic decrease in the water penetration depth of non-dewatered lime mortars as a consequence of the decrease in the particle size of fine materials. Strong water retaining ability of lime mortars have become more water releasing with the increased replacement level of copper tailings and hence greater water transfer is performed from the freshly mixed mortars into dry substrates. This enabled reduced water:binder ratios and more consolidated mixtures to be formed that resulted in a significant decrease in the water penetration depth of lime mortars containing increased replacement level of copper tailings.

It is shown in Figure 11b that increase in the replacement of level of copper tailings resulted in an increase in the water penetration depth of dewatered cement mortars as a result of the increased water:binder ratios of the resulting mixture following dewatering. The associated porosity values of dewatered cement mortars have shown to possess a good correlation with the water penetration depth of cement mortars. At 20% replacement level, dewatering cement mortars resulted in a 61% and 38% of increase in water penetration depth and porosity respectively. It is also shown in Figure 11b that

increase in the replacement level of copper tailings resulted in a considerable decrease in the water penetration depth of dewatered lime mortars and that the associated porosity values are in good correlation with these physical measures. At 20% replacement level again, dewatering lime mortars resulted in a 24% and 44% of decrease in water penetration depth and porosity respectively. Achievement of more water releasing characteristics of lime mortars due to the presence of copper tailings is mainly responsible from the reduced water penetration depth and porosity of these dewatered mortars.

4.9 Resistance to Freezing and Thawing

The resistance to freezing and thawing action of mortars containing increased replacement level of copper tailings are investigated in this section. Compressive strength loss, representing the resistance to freezing and thawing action of mortars are calculated based on the compressive strength of control specimens that were cured in the laboratory environment and were never subjected to freezing and thawing actions. Compressive strength loss of cement and lime mortars containing copper tailings are shown in Figures 12a and b respectively. Figure 12a shows that increase in the replacement level of copper tailings resulted in a decrease in the compressive strength loss of non-dewatered cement mortars. The decrease in the compressive strength loss of cement mortars containing increased replacement level of copper tailings is an indication of the increased resistance attained to freezing and thawing action. This feature is attributed to the development of more consolidated and less porous mortars that exhibited higher strength and consequently reduced compressive strength loss when subjected to freezing and thawing action. Improvement on the durability of such materials, governed by the reduced permeability of the consolidated matrix, are in agreement with Najimi et al [73].

Dewatering that enabled reduced water:binder ratios of mortars to be generated resulted in a reduced compressive strength loss and hence demonstrated an improved performance attained under the freezing and thawing action. It must however be noted that increase in the replacement level of copper tailings resulted in a more water retaining mixtures and therefore higher water:binder mortars to be generated that provided less resistance to freezing and thawing action of these mortars.

Figure 12b shows that increase in the replacement level of copper tailings resulted in a decrease in the compressive strength loss of both dewatered and non-dewatered lime mortars indicating the increased resistance attained to freezing and thawing action. The incorporation of copper tailings and hence the increased strength is mainly responsible from the increased resistance of non-dewatered lime mortars containing copper tailings. The incorporation of copper tailings along with the accelerated development of more consolidated and less porous mortars as a result of dewatering are then responsible from the higher resistance attained to freezing and thawing action of dewatered lime mortars examined in this paper.

4.10 Thermal Conductivity

Thermal conductivity of mortars containing copper tailings are shown in Figure 13. It is shown in Figure 13 that increase in the replacement level of copper tailings resulted in a slight increase in the thermal conductivity of non-dewatered cement mortars due to the decreased porosity attained in these mortars. Thermal conductivity of dewatered cement mortars, on the other hand, decreased significantly with the increased replacement level of copper tailings as a result of the decreased water loss and hence the development of more porous mixtures. Increase in the replacement level of copper tailings coupled with the reduced water:lime ratios attained following dewatering resulted in a considerable increase in the thermal conductivity of lime mortars. It must however be noted that lime mortars containing copper tailings have better thermal insulation characteristics compared to that of cement mortars due to the smaller thermal conductivities obtained in these mortars. It should also be emphasised that the use of copper tailings and therefore the reduced degree of dewatering also played a significant role in the decrease in thermal conductivity and therefore the attainment on the better thermal insulation materials for construction practice.

4.11 Cost Efficiency

The influence of the use of copper tailings and therefore the effect of dewatering on the cost efficiency of cement and lime mortars are shown in Figures 14a and b respectively. Figure 14a shows that increase in the replacement level of copper tailings resulted in a systematic increase in the cost efficiency of non-dewatered cement mortars as a result of the increase in strength and a corresponding decrease in the total cost of these mortars. The cost efficiency of dewatered cement mortars, on the other hand, are decreasing systematically with the increase in the replacement level of copper tailings. Mortars are becoming more water retaining with the increase replacement level of copper tailings and therefore possess high water:cement ratio that result in a considerable decrease in the strength of these mortars. The decrease in the compressive strength of dewatered mortars are predominantly responsible from the reduction in the cost efficiency of these mortars.

Figure 14b shows that increase in the replacement level of copper tailings resulted in a systematic increase in the cost efficiency of both dewatered and non-dewatered lime mortars. The increase in the cost efficiency of non-dewatered lime mortars are mainly due to the increased compressive strength attained by the presence of copper tailings as well as the corresponding decrease in the total cost of these mortars. The increase in the replacement level of copper tailings resulted in the formation of more water releasing mortars and therefore possess reduced water:lime ratios that caused a considerable increase in the compressive strength of dewatered lime mortars. The greater increase in the cost efficiency of dewatered lime mortars therefore attained as a result of the significant increase in the compressive strength and a corresponding decrease in the total cost of these mortars. It must be noted that the cost

efficiency of lime mortars shown in Figure 14b are much smaller than the ones demonstrated in Figure 14a due to the fact that the lime mortars have considerably low compressive strength than that of cement mortars.

5. Conclusion

The paper comprises a comprehensive study, for the first time, on dewatering wet mortars by means of copper tailings attained from Lefke-Xeros area of Cyprus and its influences both on the fresh and hardened properties of these mortar. The resulting conclusions are drawn from this study:

- Characterization study conducted on the raw materials examined in the paper indicated the compatibility of the utilization of copper tailings, obtained from the abandoned mine site of Lefke-Xeros area of Cyprus, in cement and lime mortars.
- The use of copper tailings as a binder replacement in cement and lime mortars, significantly influenced the transfer sorptivity and water loss of these mortars. The incorporation of copper tailings was vital to enhance the mortar/substrate optimisation in masonry construction.
- Increase in the replacement level of copper tailings resulted in a systematic decrease in the consistency of cement mortar. Consistency of lime mortars on the other hand increased with the increasing replacement levels of copper tailings. Dewatering decreased the consistency of cement and lime mortars as a result of the reduced water:binder ratio of the mix.
- Setting time of both cement and lime mortars are decreased with the increase replacement levels of copper tailings. The differences observed in setting time of dewatered and nondewatered mortars in each case were correspondence with the water loss of these mixtures.
- The use of copper tailings has shown to increase the compressive strength of both cement and lime mortars however, the effect of dewatering due to the increase replacement levels of copper tailings have adversely influenced the strength development of cement mortars. High water releasing ability of cement mortars have become more water retaining and hence caused in an increase in the water:binder ratio of the resultant mix with the increase replacement level of copper tailings. This feature resulted in a systematic decrease in the compressive strength of cement mortars containing copper tailings. Lime mortars, on the other hand, became more water releasing with the increase replacement level of copper tailings and hence resulted in a substantial decrease in the water:binder ratio and consequently increase in compressive strength of these mortars.
- Flexural strength and split tensile strength of mortars containing copper tailings were in a good correlation with the compressive strength of these mortars as dewatering had similar influence on the strength development of these materials.

- Shear bond strength test conducted using mortars containing copper tailings for the first time, evidently demonstrated the application of these wet mixes on the absorbent substrates. Transformation of water retaining characteristics resulted in a slight decrease in the shear bond strength of cement mortars whereas the shear bond strength of lime mortars resulted in an increase due to the formation of water releasing mortars comprising copper tailings.
- Water penetration depth and porosity experiments performed prior to the measurements of freezing and thawing resistance of mortars containing copper tailings provided insights into actual dewatering incidences and its influences on the resistance to freezing and thawing of these mortars.
- The use of copper tailings and therefore the reduced degree of dewatering have shown to play a substantial role in the decrease in thermal conductivity and improved thermal insulation properties of lime mortars compared to that of cement mortars.
- Cost efficiency of cement and lime mortars containing copper tailings along with the mechanical properties and durability characteristics reported in this paper significantly contribute in the development of environmental sustainability and socio-economic development of Lefke-Xeros area of Cyprus by means of incorporating waste copper tailings also to support sustainable development of construction materials.

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Figure Captions:

Figure 1: Copper tailings obtained from the Lefke-Xeros area of Cyprus.

Figure 2: The map of the study area designating the tailings ponds

Figure 3: Particle size distribution of hydrated lime, cement, copper tailings and sand

Figure 4: Scanning electron microscope image of the copper tailings

Figure 5: Transfer sorptivity and water loss of mortars containing copper tailings.

Figure 6a: Consistence of cement mortars containing copper tailings.

Figure 6b: Consistence of lime mortars containing copper tailings.

Figure 7a: Setting time of cement mortars containing copper tailings

Figure 7b: Setting time of lime mortars containing copper tailings.

Figure 8a: Compressive strength of cement mortars containing copper tailings

Figure 8b: Compressive strength of lime mortars containing copper tailings

Figure 9: Flexural strength versus the split tensile strength of mortars containing copper tailings

Figure 10: Shear bond strength of mortars containing copper tailings

Figure 11a: Water penetration depth of dewatered and non-dewatered mortars containing copper tailings.

Figure 11b: Water penetration depth and porosity of dewatered mortars containing copper tailings.

Figure 12a: Compressive strength loss of cement mortars containing copper tailings due to the freezing and thawing action

Figure 12b: Compressive strength loss of lime mortars containing copper tailings due to the freezing and thawing action

Figure 13: Thermal conductivity of mortars containing copper tailings

Figure 14a: Cost efficiency of cement mortars containing copper tailings

Figure 14b: Cost efficiency of lime mortars containing copper tailings

Table Captions:

Table 1: Mix constituents of cement and lime mortars incorporating copper tailings (g)

Table 2: Chemical composition of hydrated lime, cement and copper tailings (wt%)

Table 3: Heavy metal content (mg/kg) and physical properties of copper tailings

Table 4: Cost efficiency of cement and lime mortars incorporating copper tailings