Review Article

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Utilization of tailings in cement and concrete: A review

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Abstract: One of the advantages of cement and the cement concrete industry in sustainability is the ability to utilize large amounts of industrial solid wastes such as fly ash and ground granulated blast furnace slag. Tailings are solid wastes of the ore beneficiation process in the extractive industry and are available in huge amounts in some countries. This paper reviews the potential utilization of tailings as a replacement for fine aggregates, as supplementary cementitious materials (SCMs) in mortar or concrete, and in the production of cement clinker. It was shown in previous research that while tailings had been used as a replacement for both fine aggregate and cement, the workability of mortar or concrete reduced. Also, at a constant water to cement ratio, the compressive strength of concrete increased with the tailings as fine aggregate. However, the compressive strength of concrete decreased as the replacement content of the tailings as SCMs increased, even when tailings were ground into smaller particles. Not much research has been dedicated to the durability of concrete with tailings, but it is beneficial for heavy metals in tailings to stabilize/solidify in concrete. The clinker can be produced by using the tailings, even if the tailings have a low SiO_2 content. As a result, the utilization of tailings in cement and concrete will be good for the environment both in the solid waste processing and virgin materials using in the construction industry.

Keywords: Tailings; Cement; Concrete; Clinker

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1 Introduction

Mining is a fundamental industry in the development of human society, playing an important role in the economies of many countries around the world. There is little to question the value of mining to society. However, during mining, processing and metallurgical processes, it generates more and more solid wastes, which mainly include waste rock, tailings, and slag as shown in Figure 1.

Tailings are a by-product of the ore beneficiation processes. After minerals or metal of value has been extracted from ore, the residuals rich in gangue minerals are discharged as tailings with the associated process water, which contains processing chemicals. Tailings as a form of the slurry are pumped through a pipeline from the concentrator to the nearby storage facilities, which include cross valleys, hillside dams, raised embankments/impoundments, and dry-stacking of thickened tailings on land [2]. Tailings in the ponds are separated from the process water under pressure filter or gravity and the water is recycled into the extraction process. However, with the efficient grinding of ores, the sizes of tailings particles are becoming finer and finer, coupled with certain clay minerals absorbing water into its internal structure, thus the tailings are extremely difficult to separate from the water [3].

Accompanied by the progress of human civilization, the demand for mineral products is increasing for better living standards worldwide, thus more and more ores are mined. Coupled with the fact that ore grades are lower than before, the scale of ore beneficiation is becoming

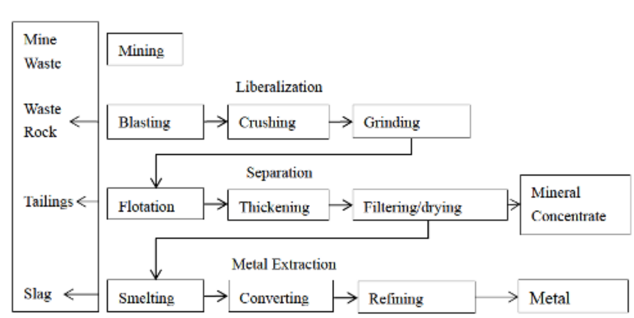

Figure 1: Mineral extraction from mining to metal [1]

larger. As a result, more and more tailings are being and will be produced in the foreseeable future. According to Jones *et al.* [4], 14 billion tonnes of tailings are produced annually worldwide. The Chinese government published a report that the number of tailings produced in China in 2013 was 1.649 billion tonnes and that the accumulated stock of tailings in China reached up to 14.6 billion tonnes by the end of 2013 [5]. Some of the tailings in the form of slurry contain metals, sulphide mineralization, and processing chemicals, which affect groundwater and surface water by seepage [6]. Failure of the tailings dams may lead to serious consequences. For example, the collapse of the Fundão Dam killed 18 people and contaminated coastal areas of Atlantic Ocean [7]. Similarly, more than 270 people died at the fall of the tailings dam that happened in Shanxi Province, China in 2008. When dry tailings are stacked together, they occupy a lot of land area, and may affect the air quality by the wind.

However, not all tailings are hazardous wastes and they can be a significant resource, for they have many useful constituents. A lot of research has been done on how to use tailings as a component for all kinds of materials. Cement Paste Backfill (CPB) may be the most important application, which can be backfilled into abandoned open pit mines or as ground support in underground mines [8]. The technology of CPB can utilize the storage of up to 60% of the tailings, but the other 40% of the tailings will still remain and thus an alternative method to reuse the tailings must be found [9]. A lot of research focuses on the applicability of metals recovery by reprocessing tailings [10, 11], but it cannot dramatically reduce the storage amount of tailings after metals are recovered [12]. The overall utilization of reduced storage amount of tailings has become the focus of research as construction materials, for instance it is used in brick [13, 14], autoclaved aerated concrete [15, 16], ceramics [17], glass [18], and geopolymers/alkali-activated materials [19], *et al.*

As a matter of fact, Portland cement concrete is still one of the most important construction materials in the world, for the production of cement went up to 4.1 billion tonnes in 2017 [20]. It is estimated that more than 10 billion cubic meters of concrete are produced worldwide, according to the cement output, and meanwhile the innovation of cement and concrete mix constituents provides a chance to reuse or recycle solid wastes. If the tailings as one of the solid wastes are used in cement and concrete, it not only helps to reduce the storage amount of tailings, but also is beneficial to the sustainable development of the cement and concrete industry. The aim of this review is to re-assess the potential utilization of tailings for cement clinker production and the opportunities and challenges of using tailings as aggregate or supplementary cementitious materials (SCMs) in cement and concrete, so it helps to better reuse and/or recycle tailings.

2 Properties of tailings

Tailings are just a general term, and the types of tailings include but are not limited to metal tailings from iron, copper, gold, lead, zinc processing; and nonmetal tailings from oil sand, quartz, phosphate, forsterite processing according to their ore deposit. The types of tailings can be also classified into classes depending on the refining methods of minerals, known as gravity tailings, flotation tailings, magnetic tailings, and chemical tailings in the extractive industry. However, the chemical compositions of tailings are highly variable according to their types of tailings. Table 1 summarizes the chemical compositions of tailings obtained from different sources. The chemical composition of tailings primarily consists of SiO_2, Al_2O_3, CaO, and Fe_2O_3 and so on. However, the contents of all oxides have a large variation range in different types of tailings. For example, the content of SiO_2in phosphate tailings is 2.1, in contrast to the 75.23 in iron ore tailings. Even if there were all lead-zinc tailings or iron ore tailings, the variation content of SiO_2 is 15.50-69.92 in the lead-zinc tailings or 24.19-75.23 in the iron ore tailings. As a result, if tailings are only classified according to their ore bodies or their refining methods, it is not sufficient for material researchers to understand the nature of tailings and to reuse tailings.

The tailings are also very diverse in mineral phases even in the lead-zinc tailings. Figure 2 presents the XRD pattern of lead-zinc tailings coming from different resources. Previous research [21] reveals that the mineral phases of the lead-zinc tailings include calcite, dolomite, quartz, kaolinite, galena, pyrite and gypsum, whereas other research [34] exhibits that there are two types of different lead-zinc tailings – one type has quartz, orthoclase, barite, albite, and chlorite as the main minerals phases; and the other has dolomite, calcite, barite, and quartz. The mineral phases of pyrite tailings include kaolinite and pyrite [35], but the main mineral phases of phosphate tailings are dolomite and apatite, according to XRD patterns [32] shown in Figure 3 and Figure 4.

The physical properties of tailings are less different among all kinds of tailings compared to the chemical compositions and mineral phases of tailings. The size fractions of tailings are classified as “sand”, “silt”, and “clay” based on a variety of methods and standards in many mining operators [3]. With the progress of grinding technology, there

Table 1: Chemical compositions of tailings (wt. %) used from the literature

References	Type of tailings	Sources	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
Nouairi, *et al.* [21]	Zn-Pb tailings	Tunisia	15.5	6.56	5.91	19.9	3.99	21.9	0.33		15.1
Zhang, *et al.* [22]	Zn-Pb tailings	China	69.92	10.41	1.89	2.19	1.39	0.55	2.17	0.51	3.68
Argane, *et al.* [23]	Zn-Pb tailings	Morocco	68.44	9.38	2.2	1.99	0.48	0.449	5.46	0.7	
Jankovic, *et al.* [24]	Zn-Pb tailings	Serbia	43.26	11.11	15.57	20.01	4.31	0.32	1.00	0.92	5.61
Cheng, *et al.* [25]	Iron tailings	China	75.23	2.64	11.31	1.47	2.10	0.08	0.40	0.49	
Fontes, *et al.* [26]	Iron tailings	Brazil	24.19	4.82	45.92						4.06
Shettima, *et al.* [27]	Iron tailings	Malaysia	56	10	8.3	4.3			1.5		3.3
Zhao, *et al.* [28]	Iron tailings	China	52.06	17.14	9.13	12.74	3.68		0.3	0.97	3.23
Thomas, *et al.* [29]	Copper tailings	India	75.0	12.16	3.60	0.16	0.49		1.85	4.297	2.10
Kiventera, *et al.* [30]	Gold tailings	Finland	49.9	10.4	9.7	11.1	5.9		1.3	3.0	12.9
Ye *et al.* [31]	Bauxite tailings	China	32.24	37.39	8.67	3.15	0.85				13.74
Zheng, *et al.* [32]	Phosphate tailings	China	2.1	0.1	0.8	36.8	18.9	1.0		0.1	35.8
Pyo, *et al.* [33]	Quartz-based tailings	Korea	79.53	9.52	3.22	0.51	0.64		3.24	0.72	2.46

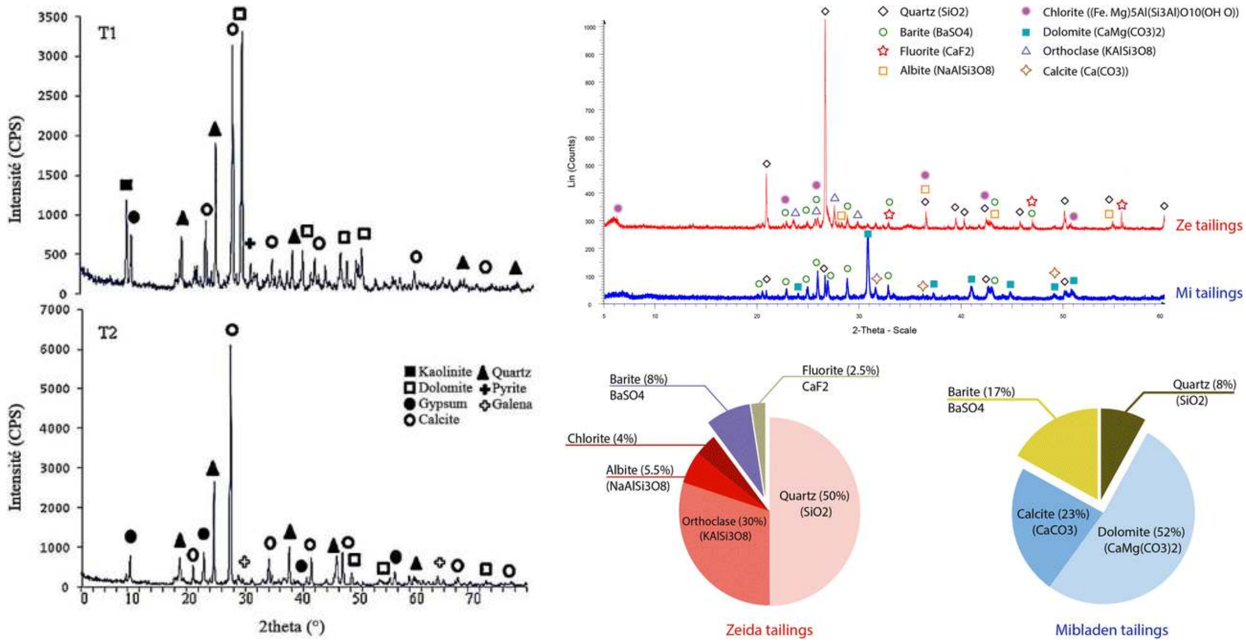

Figure 2: XRD pattern of lead-zinc tailings [21]/[34]

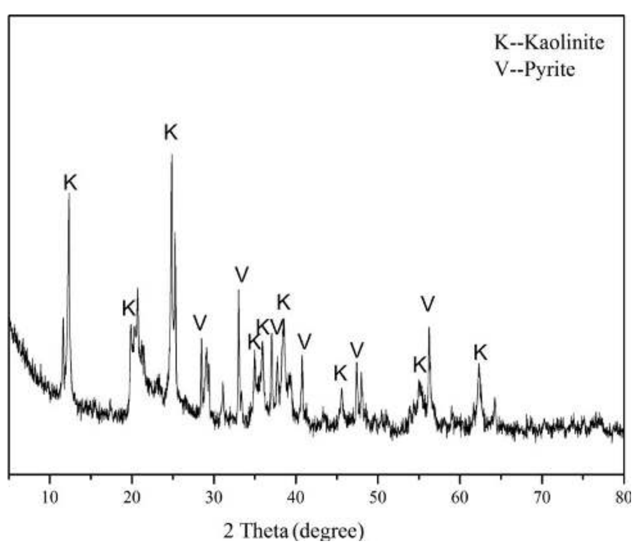

Figure 3: XRD pattern of pyrite tailings [35]

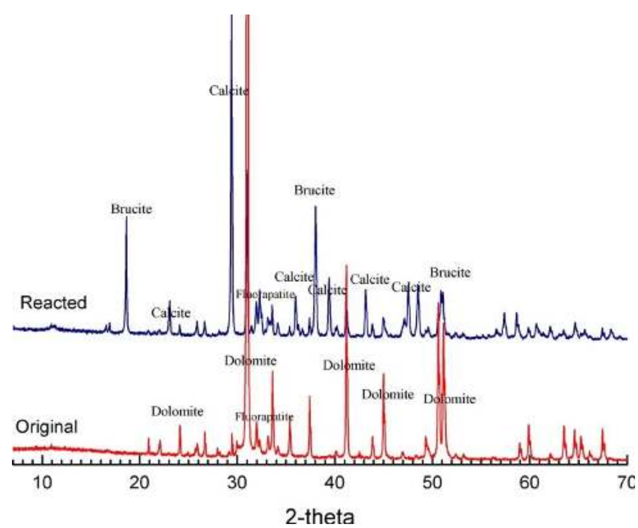

Figure 4: XRD pattern of phosphate tailings before and after alkali-treatment [32]

are more and more “silt” and “clay” in the tailings, and even if tailings are used as aggregate, the maximum size of tailings is less than 1 mm in some literature [34, 36]. In general, the tailings have a highly rough and irregular surface [28], since the grindability of various mineral phases in the tailings is different. Due to the mineral phases, the tailings have a varied density and water absorption, which is also remarkably affected by the particle size as shown in Figure 5.

3 Utilization of tailings as aggregate

In general, concrete includes coarse aggregate and fine aggregate, but tailings are merely used as partial or full replacements of fine aggregate, since their particles are fine with a diameter less than 1 mm. The physical properties of tailings have a significant impact on the workability, density, dimensional stability, strength, and durability of concrete. Sometimes tailings, especially metallic

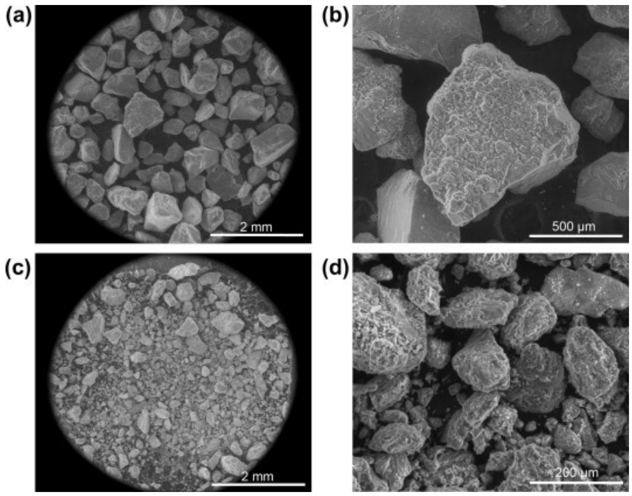

Figure 5: SEM images of iron ore tailings [28]

tailings, contain a thimbleful of deleterious heavy metal, which may cause environmental concerns or modify the hydration processes and durability of mortar or concrete mixtures [37, 38].

3.1 Effect on fresh properties

Workability, which is defined as the ease of transportation, placement, compaction and finishing of the mixture, is an important property of fresh mortar or concrete mixtures [39]. It was found that the flow of mortar decreased with increasing tailing substitution levels because tailings had a finer particles size distribution which raised the total specific surface area of fine aggregates [26, 38, 40]. A similar consequence applied to concrete. A decrease in a slump was observed up to the inclusion of 100% tailings substitution as fine aggregate. This might be attributed to particle size and surface texture of tailings, which may demand more water and hence reduce the workability [27, 40, 41].

The setting time of mortar extended when the tailings were incorporated as a replacement of fine aggregate, for the heavy metals in tailings retarded the hydration of cement by forming a low permeability layer around cement clinker un-hydrated grains [23]. The utilization of tailings as fine aggregate replacement enhanced the density of fresh mixtures, for the reason of the increase was attributed to the higher specific gravity of tailings than that of natural sand [29, 41]. Besides that, Fontes *et al.* [26] considered that the increased packing of the grains was also a reason due to more fines content in mixtures comprising tailings.

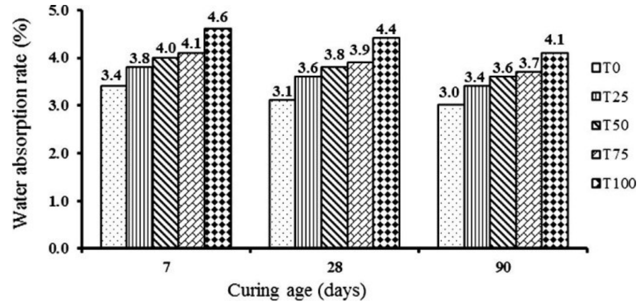

Figure 6: Water absorption in concrete with and without iron ore tailings [27]

3.2 Effect on hardened properties

Similar to the fresh mortar or concrete mixtures, researchers noticed an increase in the densities of hardened mixtures when tailings, such as iron ore tailings [36], lead-zinc tailings [38], and copper tailings [29], were used as an aggregate replacement. Also, as a result of a higher specific gravity of tailings, mortar prepared with fractional replacement content of aggregate by tailings was proved to be effective in radiation shielding [42].

Water absorption is a physical property of hardened mortar or concrete and is related to the porosity of mortar and concrete. Most published research has revealed that mortar or concrete containing tailings as fine aggregate had a higher water absorption percentage due to capillarity [26] or higher fine content and specific surface area values of tailings [38]. Shettima *et al.* [27] described that concrete with tailings absorbed more water than control specimen; but water absorption decreased with increase in the age as shown in Figure 6, for the tailings occupied the macro and micro pores in the mix. However, Sant'ana *et al.* [36] confirmed that the water absorption of concrete reduced up to the inclusion of 80% tailing substitution as fine aggregate, for tailings occupied the pores of the cement paste because of the fill effect. The variation of water absorption and porosity of concrete using tailings as aggregate is shown in Figure 7. In contrast, other researchers [23, 28] displayed different results about the porosity, and they considered that the total porosity increased with an increase of the tailings content as illustrated in Figure 8.

Mechanical properties, which include compressive strength, flexural strength, tensile strength, adhesive strength and so on, are the most common assessments for hardened concrete. Utilization of tailings as aggregate in mortar and concrete presented various effects on the compressive strength. With a constant water to cement ratio, the compressive strength of mortar or concrete incorporat-

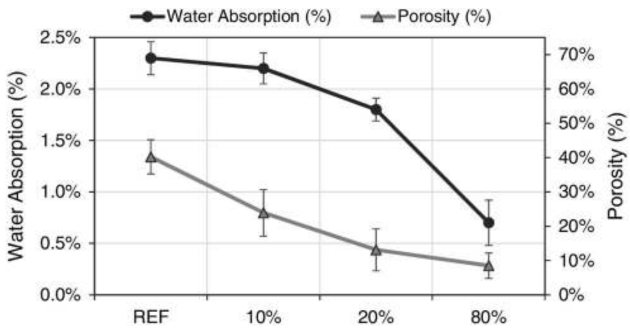

Figure 7: Water absorption and porosity results [36]

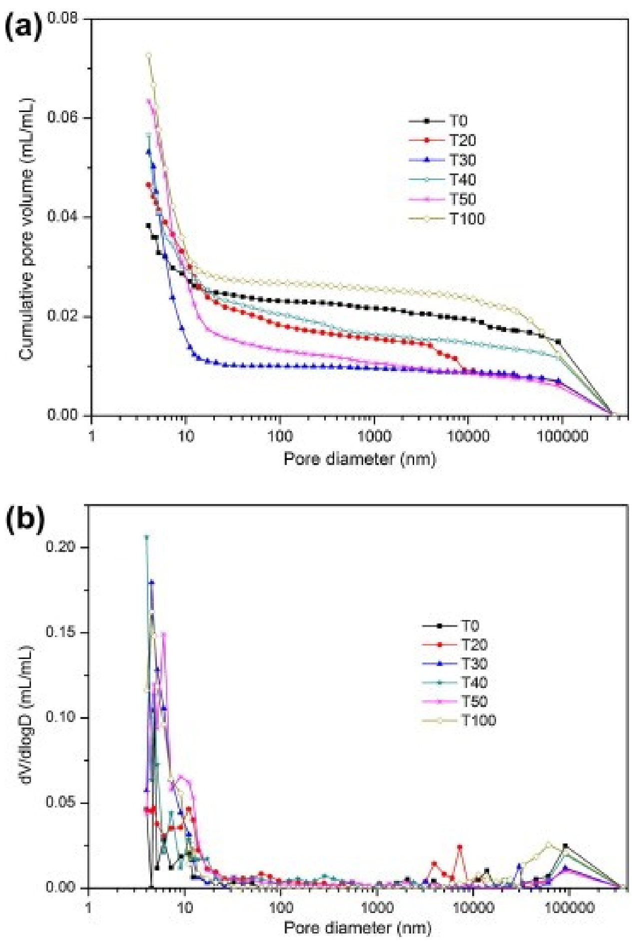

Figure 8: Pore size distribution of mortar containing iron ore tailings [28]

ing tailings was found to increase for those including up to 100% tailing substitutions with respect to control specimens. For example, the compressive strength of mortar with 100% tailings as a fine aggregate was 13% higher than that for the control specimen [26], whereas the percentage increase of concrete compressive strength relative to control was 10.2% for 75% tailings substitution at 28 days. Lv *et al.* [43] came to a similar conclusion to Fontes' research. Authors concluded that this was due to the finer particles of tailings which filled the pores and optimized the pore structure [27]. Table 2 demonstrates the increase of compressive strength of concrete with tailings. Fisonga *et al.* [44], Sant'ana *et al.* [36] and Thomas *et al.* [29] observed that the compressive strength of concrete improved with increasing tailing contents, but beyond a limited replacement content of fine aggregate, the compressive strength of concrete decreased. Figure 9 shows that the replacement threshold of fine aggregate possibly relates to the water to cement ratio and ages. Since the tailings need more water to achieve the same workability, mortar or concrete containing tailings as fine aggregates had a higher water to cement ratio than the control specimens, which lead to the compressive strength decrease when tailings were utilized as fine aggregates [28, 45]. The utilization of 10% tailings as fine aggregates in mortar or concrete, even at the same water to cement ratio as well as the control specimens, reduced the compressive strengths, and the authors described that the loss of strength was mainly related to the retarding effect of heavy metal in tailings [36, 38].

Table 2: Compressive strength of concrete with and without tailings

Curing age (days)	T0	T25	T50	T75	T100
7	32.0	31.9	30.2	32.8	29.3
14	34.3	35.7	35.3	35.1	33.1
28	38.0	42.9	42.0	41.9	38.5

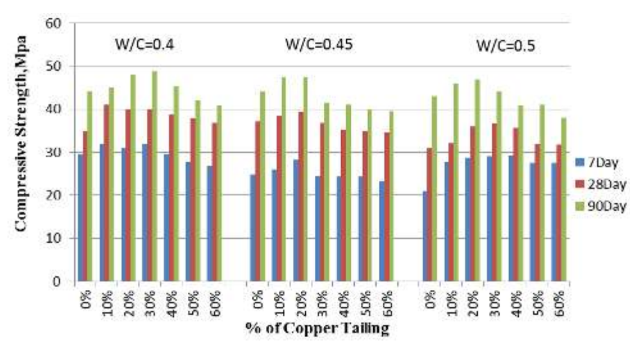

Figure 9: Compressive strength of concrete containing tailings [29]

For flexural strength, Xu *et al.* [40] and Thomas *et al.* [29] considered that there was also a threshold of tailings substitution for a constant water to cement ratio as showed in Figure 10, but other authors confirmed that the flexural strength rises with the utilization of tailings up to 100% replacement of fine aggregate [41]. The same was found to be true for tensile strength. Shettima *et al.* [27] considered that a 25% tailing substitution as a fine aggregate was the optimum concentration for the tensile strength of concrete, and the tensile strengths of concrete with tailings were always higher than the control concrete. In contrast, Gallala *et al.* [42] reported that the tensile strength decreased for the concrete containing tailings as fine aggregate, and only at 20% and 25% replacement of fine aggregate with tailings, the tensile strength of concrete was very close to the control specimen.

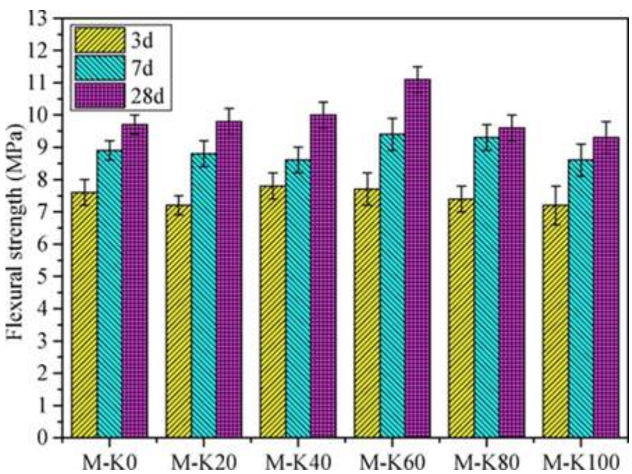

Figure 10: Flexural strength of mortars [40]

There were different variation trends for the drying shrinkage of concrete with tailings as fine aggregate among different authors. Gupta *et al.* [41] noticed that the shrinkage strains of all the concrete with 10%-80% tailings as a fine aggregate were higher than those of the control. Thomas *et al.* [29] found a decreasing trend in shrinkage strain value from 10% to 30% tailings substitution as fine aggregate, and beyond that replacement content, the value started to increase at 7, 28, 56 and 91 days when water to cement ratios were 0.4 and 0.5. In contrast, Shettima *et al.* [27] presented the opposite results of drying shrinkage to the research of Gupta, and revealed that all drying shrinkage of concrete with tailings were lower compared to control concrete. The mortar was used to test the drying shrinkage by Argane *et al.* [38], and authors observed that similar drying shrinkage results were obtained for mortars with tailings as fine aggregate and control mortar.

3.3 Effect on durability performance

The abrasion resistance of concrete sometimes refers to wear on pavements and industrial floors by vehicular traffic, and the abrasion resistance test is done to measure the mass loss or the depth of wear. Sant'ana *et al.* [36] confirmed that the mass loss of concrete increased with an increasing percentage of the tailings. However, for the replacement of fine aggregate by 10% and 20% tailings, there was a smaller mass loss than control concrete. Other authors also have similar results. Gupta *et al.* [41] detected that the utilization of 10% tailings as fine aggregate had a lower depth of wear of the concrete with tailings than control specimen. When the water to cement ratio was 0.4 and 0.5, the least abrasion could be observed at a 20% tailing substitution as a fine aggregate [29].

The permeability, defined as the rate of viscous flow of fluids or other potentially deleterious substances under pressure through the pore structure, has an important effect on the durability of concrete. The use of 10% tailings as fine aggregate in concrete had much the same water permeability compared to that of control concrete, but the water permeability of concrete increased gradually as the percentage of tailings reached up to 80% [41]. Other authors had similar results in water permeability, but due to the denser packing of tailings in concrete for tailings substitution, the air permeability of concrete decreased continually with the increasing of tailings substitution as a fine aggregate [29]. For chloride ion penetration in concrete, Shettima *et al.* [27] observed that concrete including tailings had higher chloride ion permeability than control concrete, but Thomas *et al.* [29] confirmed that the chloride ion permeability decreased continuously from the control concrete till 30% substitution for 0.4 or 0.5 of the water to cement ratio and the reason was the tailings reducing the pores of concrete.

Thomas *et al.* [29] researched the resistance of concrete to sulphate attack and noticed that the concrete with tailings was similar to the control specimens, in which they were resistant against sulphate attacks. In contrast, Shettima *et al.* [27] using 5% H_2SO_4 solution described that the weight of concrete containing tailings decreased more than the control specimens and considered that the fineness of tailings and the direct attack on the aluminosilicate framework by breaking the bonds were the reasons for concrete with tailings decreasing the weight. At the same time, the authors also found that carbonation depth decreased as the percentage of tailings in concrete mixes increased. However, Gupta *et al.* [41] revealed that the carbonation depth of concrete increased with increasing replacement amounts of tailings.

4 Utilization of tailings as supplementary cementitious material

The process of cement production consumes a lot of energy and emits a significant amount of CO_2. To lessen these amounts, all kinds of industrial solid wastes containing high silica are used to replace cement as supplementary cementitious materials (SCMs), such as blast furnace slag [46], fly ash [47], steel slag [48], *et al.*, in cement mixes. The chemical composition of tailings, as presented in Table 1, shows that some tailings have high silica content. In addition, the particle size of tailings is about the same size as cement particles, so some researchers [49–52] focus on the properties of concrete containing tailings as SCMs for partial replacement of cement.

4.1 Treatment of tailings

SCMs are either pozzolanic, cementitious, or both cementitious and pozzolanic. However, due to the poor cementitious property of tailings, several important steps of treatment should be considered prior to the utilization of tailings in concrete as SCMs, namely: drying, grinding, and/or calcining. Unfortunately, very few research papers in the concrete industry have discussed how the tailings are dried. Only Onuaguluchi *et al.* [53, 54] describes that the tailing samples were air dried and then sieved with a 600 μm sieve. Other researchers [55] suggested that the tailings only passed a 45μm square hole sieve as a treatment method before it was used.

Some research [56, 57] used grinding as a treatment method for tailings, and the representative particle size distributions of the tailings are given in Figure 10 after the tailings were ground at different durations [58]. Meanwhile, with the decrease of particle size and the increase of specific surface area after grinding, the internal structure and physical and/or chemical properties of tailings may change as well [25]. Besides, tailings mixed with some chemical activators were ground together by a ball mill and this is mechanical and chemical activation of tailings [59].

Calcination is the other treatment method for tailings [60, 61]. Through the calcining process, some of the minerals in tailings decompose and the crystal structures of minerals are destroyed, while amorphous minerals arise, which have high pozzolanic activity [62, 63]. Sometimes, tailings were mixed with other solid waste and then calcined together to prepare new SCMs [64, 65]. Grinding and calcining can be used together for the treatment of tailings. Cumulative heat of untreated and treated tailings and relation between mass loss under 650°C and increase in pozzolanic capacity were shown in Figure 12 [66].

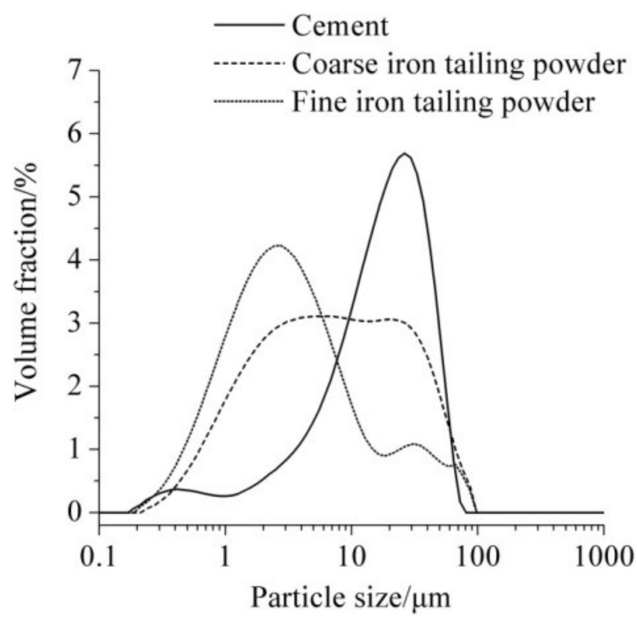

Figure 11: Particle size distributions of tailings after grinding during the different time [58]

4.2 Effect on hydration reactions

The foundation of using tailings as SCMs for partial replacement of cement is based on the hydration reaction of tailings with $Ca(OH)_2$ in cement paste, so the $Ca(OH)_2$ content can assess the reaction of tailings in cement paste. Cheng *et al.* [25] figured out the contents of $Ca(OH)_2$ in hardened cement paste with tailings substitution as SCMs by using TG-DTA technology and the authors found that the content of $Ca(OH)_2$ in control hardened cement paste was 21.367%, whereas the contents of $Ca(OH)_2$ were 16.856% and 15.064% in hardened cement-tailings paste with tailings substitution amounts 20% and 30% respectively. They concluded that it is the pozzolanic activity of tailings which causes the secondary hydration reaction. Wong *et al.* [63] also displayed that the tailings were effective in reducing the amount of $Ca(OH)_2$ in blended cement paste, but the pozzolanic activity of tailings in blended cement paste was lower than silica fume and metakaolin.

The total amount of heat liberated and the rates of heat liberation from hydration of cement paste can be used as indices of cement reactivity. Han *et al.* [58] determined the heat of hydration of cement paste blended fine tailings and coarse tailings at varying water to cement ratios. The rates of heat liberation and the cumulative amount of heat liberated are shown in Figure 11. The authors considered that the heat of hydration of tailings was very low at an early age and that the approximately identical rates of heat liberation of cement paste with fine tailings to control cement paste, were because tailings reduced the cement content and increased the effective water to cement ratio - promoting the hydration of cement. Moreover, the fine particle size of tailings acts as a nucleation site for hydration of cement, further increases the hydration degree of the cement. Wang *et al.* [67] and Zheng *et al.* [32] obtained similar results by using cement paste blended tailings or the same content of quartz, and concluded that the effect of tailings on the whole hydration process was mainly due to the dilution effect.

4.3 Effect on fresh properties

Generally, the slump of a concrete mix decreases with increasing percentages of tailings as partial replacements of cement. Guo *et al.* [62] found that the slump of concrete declined from 150mm to 8mm with 40% tailings as replacement of cement. Wong *et al.* [63] described as well that the slump of concrete reduced from 200mm to 120mm due to a replacement of 7.5% by mass of cement with tailings. Even if mortar was used, the reduction in flow value was inversely proportional to the increase in tailings content in the mortar [68]. However, Sancak *et al.* [69] observed that the slump value improved by approximately 15mm and did not change with the tailings substitution amount from 5% to 40%. Zheng *et al.* [32] revealed that the decrease in the water demand for standard consistency of cement paste, along with the increasing tailings content in blended cement paste, contributed to the reduction in a total surface area with the tailings.

The setting time of cement paste extended up to the inclusion of 30% tailings substitution as SCMs, mainly due to the dilution effect of tailings and partially due to the phosphorus dissolution from phosphate tailings [32]. When 7.5% tailings were used as SCMs, the air content and unit weight of freshly mixed concrete were not significantly different from the control concrete [63].

4.4 Effect on hardened properties

Xiong *et al.* [55] described that owing to the pozzolanic reaction of tailings, more hydrates were generated and filled pores, which in turn decreased the porosity and critical pore diameter. Wong *et al.* [63] revealed as well that the tailings as SCMs reduced the average size of the pore diameter. In contrast, Han *et al.* [58] researched the effect of coarse tailings and fine tailings on the pore structures of a hardened paste containing tailings, and confirmed that coarse tailings increased the critical pore diameter and had a negative impact on the pore structure, but fine tailings decreased the critical pore diameter.

The utilization of tailings as cement replacement reduced the compressive strength with an increase in the proportion of the tailings, irrespective of the age of concrete or mortar [25, 32, 37, 56, 57, 69, 70]. The typical compressive strength curve is presented in Figure 12. The decrease was due to the low pozzolanic activity of tailings as SCMs even as a ground powder. Nevertheless, sometimes a certain concentration of fine tailings could enhance the compressive strength of concrete with tailings as SCMs because the fine tailings powder could fill miniscule pores to accelerate the hydration of cement, whereas other concentrations of tailings decreased the compressive strength [58, 59, 63, 71, 72]. Franco de Carvalho *et al.* [73] proved that when fine basic oxygen furnace slag tailings were used as supplementary cementitious material, the compressive strength with 20% fine tailings replacement was the highest. When 40% coarse tailings and 20% fine tailings were added, the strength was lower than that of the control concrete, but it was still close to the control concrete. By using calcined tailings in which metakaolin was created from the kaolinite, the compressive strength of concrete improved and had a maximum with an optimum concentration of tailings [35, 62]. When the tailings as an additive were not a replacement of cement, the compressive strength of concrete with tailings was higher than the control concrete owing to the filler effect [54, 74].

Wong *et al.* [63] obtained the static modulus values of rupture and elasticity of concrete with 7.5% tailings as SCMs and found that the concrete containing tailings had marginal increases in modulus values of rupture and elasticity with respect to the control concrete. Moreover, the authors also noticed that the concrete incorporating tailings as cement replacement experienced smaller shrinkage under air curing and smaller expansion under moist curing compared to control concrete. However, Zheng *et al.* [32] showed the increase in percentages of dry shrinkage in Figure 13 with a minimum when the content of tailings was 10%. The authors considered that tailings, which were

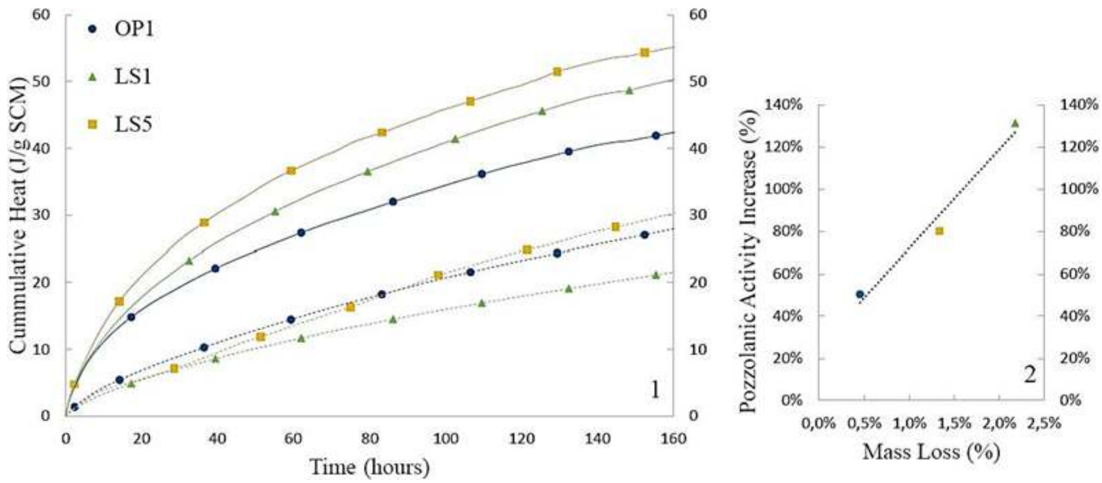

Figure 12: Cumulative heat (J/g of SCM) of untreated (dashed line) and treated (700 C, 30 min grinding) tailings. 2. Relation between mass loss under 650 C and increase in pozzolanic capacity, measured as cumulative heat release at 7 days [66]

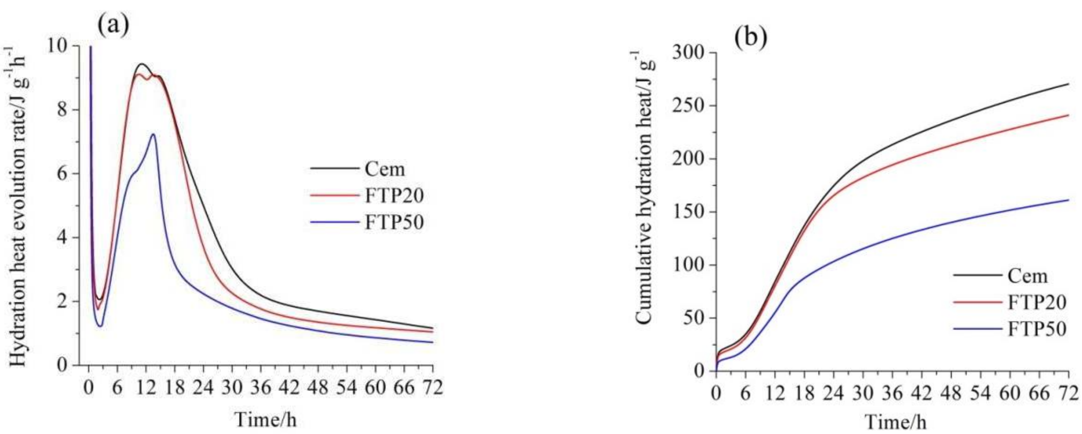

Figure 13: The heat of hydration cement paste containing fine tailings at w/c ratio of 0.4 [58]

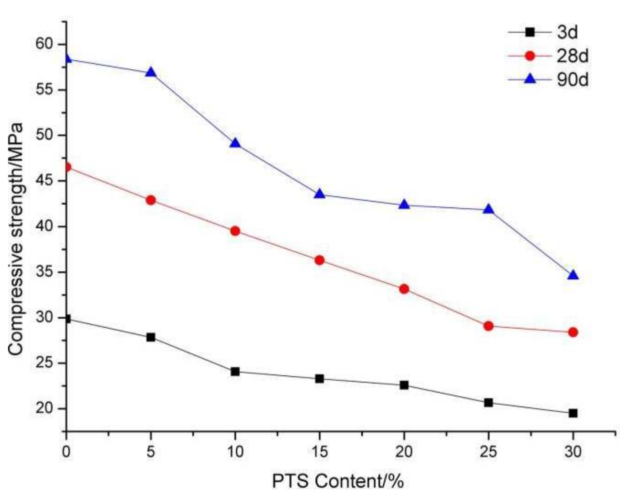

Figure 14: Compressive strength development of cement with tailings [32]

non-hydraulic, as a replacement of cement restrained the shrinkage; whereas as in cement with tailings substitution, the number of hydration products reduced and the porosity of hardened cement paste increased, thereby promoting the dry shrinkage. For autogenous shrinkage, Wang *et al.* [67] proved that with the increase of cement replacement by tailings, the autogenous shrinkage of concrete decreased to different degree. With tailings replacing 20% of cement, the autogenous shrinkage of concrete was the most. This can be explained by different mechanisms. On the one hand, the replacement by tailings restricts the cement initial hydration of concrete. On the other hand, with a further increase of the added tailings, the microstructure and strength of the concrete can be negatively affected, which may lower structuring of a stiff hydrated skeleton that can withstand internal stresses induced by capillary stress due to self-desiccation. Autogenous shrinkage of

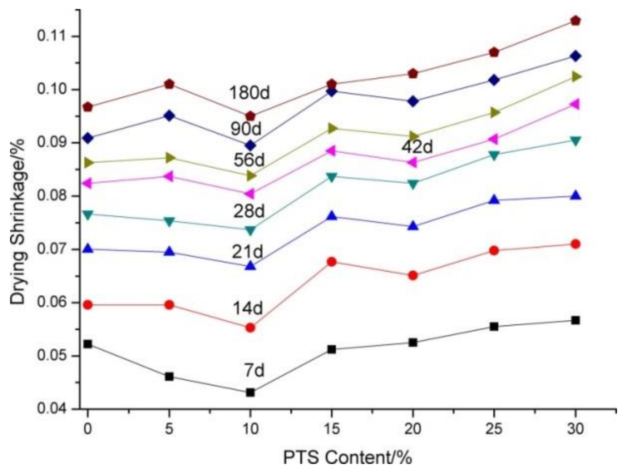

Figure 15: Effect of tailings on drying shrinkage [32]

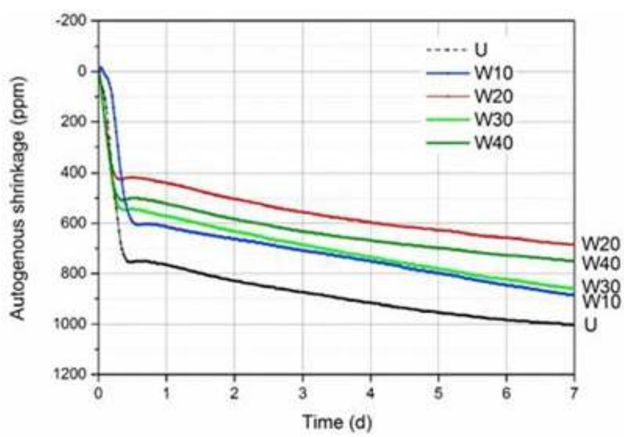

Figure 16: Autogenous shrinkage of concrete pastes with different content of tailings content [67]

concrete pastes with different content of tailings is showed in Figure 16.

4.5 Effect on durability performance

Rapid chloride permeability tests (RCPT) were conducted by Wong *et al.* [63] and the authors noticed that the addition of tailings reduced the pore sizes, thus lowering the permeability, but the permeability reduction in concrete with tailings was marginal with respect to the control. By comparison, Onuaguluchi *et al.* [54] revealed that after RCPT, the total charge transmitted through the concrete blended tailings were higher than that of the control concrete and authors confirmed the presence of copper in the tailings, which led to an increased conductivity of the concrete with tailings during the tests. However, the chloride penetration depths declined with the increase in tailings content and these results showed that the concrete incorporating tailings enhanced the chloride penetration resistance compared to the control specimens [54].

Onuaguluchi *et al.* [54] researched the mass loss of concrete specimens after exposure to the hydrochloric acid solution and displayed that the concrete containing tailings had a lower mass loss because of the secondary hydration reaction induced by tailings, which reduced the $Ca(OH)_2$ available for the acid attack in specimens. The sulfate resistance of mortar with tailings as partial replacement of cement was investigated, and slight increases in expansion values of mortars with increasing tailing substitutions were observed. The increased expansion was due to the higher water permeability of mortar with tailings and the formation of gypsum and expansive ettringite in mortar specimens compared to the control [54]. In contrast, Xiong *et al.* [55] confirmed that the tailings enhanced the sulfate resistance of cement paste in both sodium sulfate and magnesium sulfate solutions, wherein the expansion of cement pastes with tailings in sodium sulfate solution was larger than those in magnesium sulfate solution. At the same time, the cement paste with tailings had a smaller compressive strength loss when cement pastes are exposed to the sodium sulfate solution and magnesium sulfate solution [55].

Wong *et al.* [63] studied the alkali-silica reaction of mortar containing tailings and the authors found that the replacement of cement by 7.5% tailings reduced the expansion, the cracking, and surface deteriorations of mortar. After 300 cycles of freeze-thaw, the concrete containing 7.5% tailings had a higher relative dynamic modulus of elasticity and durability factor against to the control concrete [63]. According to Choi *et al.* [68], the amount of leaching of heavy metals in tailings was equal to or higher than the standard values, but the mortar containing tailings had lower leaching quantities of heavy metals, which were stabilized/solidified by the cement hydration. Through semi-dynamic leaching tests, Kundu *et al.* [37] found that the release of heavy metals decreased with an increase of the tailings content in a mortar.

5 Utilization of tailings for cement clinker production

The preparation of cement clinker, which has a huge production amount each year, has been one of the methods to deal with various solid wastes [75, 76]. Meanwhile, most of the tailings consist mainly of SiO_2, Al_2O_3, Fe_2O_3, CaO as shown in Table 1, so the tailings are used as the raw materials for cement clinker production [77–79]. The sintering temperature declined down 100-150°C by using tailings as clay for cement clinker calcinations, especially when the medium calcium limestone was used together [80]. Due to the existence of trace elements and particular mineral compositions of tailings, the utilization of tailings improved the burnability of raw materials and promoted the formation of C_3S, which enhanced the mechanical properties of cement [81, 82]. Furthermore, the usage of tailings as alumino-silicate materials promoted the solid state reactions and accelerated the reactivity of raw material [81]. For the chemical compositions of tailings were quite varied, sometimes the tailings with high SiO_2 content could not be used for cement clinker production [83], or the tailings with high amounts of impurity oxides could only be used as mineralizer, so the usage dosages of tailings for cement clinker production were less than 5% [84]. However, special cement such as sulfobelite clinker, high-belite cementitious materials was prepared with tailings with a low SiO_2 content [21, 85, 86]. On the other hand, the raw meal within 10% high-magnesium and low-silicon iron ore tailings (IOT) addition sintered at 1420°C for one hour can produce better quality cement clinker than without IOT [81, 87]. Besides, the leached heavy metals decreased considerably in clinker, so the cement clinker production by using tailings can help in the immobilization of heavy metals in tailings [21]. The concentrations of metal contaminants in the clinker are very low and there is not risk of leaching or transportation [88].

6 Discussion

Tailings are traditionally named according to their sources, the ore body, for example iron ore tailings, lead-zinc tailings, copper tailings, gold tailings, oil sands tailings, and so on. Researchers making materials often use this classification method, but it does have some limitations, for it cannot reflect the nature of the tailings and its technological characteristics. In fact, according to the mineralogical compositions and properties of tailings, it is helpful for material researchers to use tailings as recycled materials. In other words, according to the dominated mineral phases, tailings can be loosely classified as silicate minerals, carbonate minerals, feldspar minerals, clay minerals, and so on.

The treatment of tailings is the first step for using tailings as an ingredient in cement and concrete, but the fine solid particles of tailings are difficult to separate from the tailings water [3]. Thus, it is a good idea to use pre-wetted tailings as cement replacement to investigate the effect of tailings on the properties of mortar or concrete [71]. The grinding method is used as the treatment for tailings, and consumes a lot of energy. It is not better than the sieving method, for the tailings are becoming finer with the submicrometer ore grinding in the extractive industry. Moreover, through the sieving process, the coarse particles of tailings can be used as aggregate and the fine particles of tailings can be used as the replacement of cement or filler material in concrete or cement mortar. In contrast, calcination is especially suitable for tailings with high contents of kaolinite because metakaolin, which has a high pozzolanic activity, is created by calcining the kaolinite in tailings. Furthermore, the utilization of tailings in cement and concrete may increase a certain cost for the treatment of tailings before its recycled application. However, for more and more attention is focused on the harm of tailings to the environment [89, 90], the social and environmental benefits of utilization of tailings in cement and concrete should be taken into account in the future, not only the cost in using the tailings.

Generally, tailings used as partial aggregate or cement replacement has an adverse effect on the workability of fresh concrete and mortar due to the increase in the total specific area [26, 38, 62]. However, by eliminating the finer sizes of tailings as a cement replacement, the adverse effect on workability can be reduced [33]. The setting time of cement paste and mortar extended by using tailings substitution as aggregate, or SCMs, for different reasons [23, 32].

According to the summarized findings, the utilization of tailings as aggregate often resulted in an increase in the compressive strength with a constant water to cement ratio, and the main reason for the increase in compressive strength is because the tailings have a finer particle size to fill the pores of mortar or concrete. By comparison, at the same workability of mortar or concrete with tailings as fine aggregate, the compressive strength decreased, for the tailings need more water, which leads to a higher water to cement ratio. Hence, considering the compressive strength and the workability of mortar and concrete, it is generally recommended to adopt no more than 30% tailings substitution as fine aggregate based on the literature. The effect of tailings as cement replacement on compressive strength is generally negative because of the low pozzolanic activity of tailings as SCMs even if the tailings are ground. In contrast, there could be a beneficial effect on the compressive strength due to the filler effect and a high pozzolanic activity of calcined tailings, which have high kaolinite content.

Despite not having much more literature about durability performance, the utilization of tailings both as aggregate and as SCMs has a contrasting effect on the durability of concrete. The chloride ion penetration in concrete with tailings increased [27, 54], whereas other authors considered that the chloride ion permeability decreased continuously using tailings [29, 63]. A similar situation persists in the sulfate resistance and the carbonation of mortar or cement concrete with tailings [27, 41]. For the leaching amount of heavy metals, it is considered that mortar containing tailings had lower leaching quantities of heavy metals [37, 68], but there is insufficient literature available to confirm this.

Usually, tailings can be used as raw materials for cement clinker production. However, since the chemical compositions of tailings are quite varied, sometimes the tailings can only be used as a mineralizer for cement clinker production [83]. Besides, the tailings with high alkali content have not been considered for cement clinker production, and much more research on the effect of the metal in the tailings on the clinker mineral phases and the hydration products of cement prepared with tailings is needed.

7 Conclusion

The research of tailings in cement and cement concrete is currently still in its infancy and there is insufficient literature available. Following are the conclusions drawn from the literature review:

- Tailings should be characterized according to their mineralogical compositions and properties; for example silicate minerals, carbonate minerals, and feldspar minerals, for the benefit of the material researcher, and the utilization of tailings in cement and concrete should be carried out according to these classifications of the tailings.
- The sieving treatment method should be used for most of the tailings before its recycled utilization, and calcination treating is suitable for tailings with a high content of kaolinite.
- The utilization of tailings reduces the workability of concrete with tailings as fine aggregate or SCMs.
- The compressive strength of concrete increases with the tailings as fine aggregate, but it is generally recommended to adopt no more than 30% tailings substitution as fine aggregate. High percentages of tailings substitution as SCMs decrease the compressive strength of concrete except for the calcined tailings.
- There is a dispute among researchers about the durability of concrete with tailings, but it is beneficial because of the heavy metals solidification in the tailings.
- The clinker can be produced by using the tailings, and even if the tailings have a low SiO_2 content, it can be still used to prepare the special cement clinker.
- Finally, the utilization of the tailings in cement and concrete will be good for the environment both in the solid waste processing and virgin materials using in the construction industry.

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