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Review

Research Status and Prospects for the Utilization of Lead–Zinc Tailings as Building Materials

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Abstract: Lead–zinc tailings are the typical solid wastes in mines with high yield and low utilization rates in some countries at present. They are mainly stockpiled in tailings reservoirs, occupying massive land resources and threatening the health of the environment. One of the advantages of building material production in sustainability is the ability to utilize large amounts of industrial solid wastes, and the use of lead–zinc tailings in building materials is an effective way to meet the dual needs of environmental protection and economic development. This paper reviews the progress of utilizing lead–zinc tailings as building materials and mainly summarizes the status of lead–zinc tailings in cement, geopolymer, concrete, building brick, and foam ceramic. According to previous research, lead–zinc tailings contain large amounts of silica–alumina oxide, which can be used in the production of cement clinker. The addition of lead–zinc tailings to the sintered material can reduce the sintering temperature. The active components contained in lead–zinc tailings can be used in concrete instead of cement or in the preparation of geopolymers. Meanwhile, lead–zinc tailings can also be used as a fine aggregate. However, there are few studies on the durability of building materials with lead–zinc tailings. Additionally, most of the research results of building materials are in the laboratory stage, which are difficult to be promoted. In view of these problems, corresponding suggestions and prospects are given in the end in order to provide a reference for the research on the utilization of lead–zinc tailings.

Keywords: cement; concrete; geopolymer; lead–zinc tailings; research progress; resource utilization

Citation: Li, R.; Yin, Z.; Lin, H. Research Status and Prospects for the Utilization of Lead–Zinc Tailings as Building Materials. *Buildings* **2023**, *13*, 150. https://doi.org/10.3390/buildings13010150

Academic Editor: Antonio Caggiano

Received: 21 November 2022
Revised: 2 January 2023
Accepted: 4 January 2023
Published: 6 January 2023

1. Introduction

Lead–zinc tailings are the residual solid waste of lead–zinc ore after crushing and flotation [1]. China has a wide distribution of Pb–Zn minerals, and the production of Pb and Zn ranks first in the world [2]. However, with many lean ores, few rich ores, and complex mineral composition, most lead–zinc ores are highly difficult to beneficiate [3,4]. Therefore, with the continuous development of mineral resources, the number of tailings has increased dramatically [5,6]. According to the latest data in the Annual Report on Comprehensive Utilization of Resources in China, by the end of 2021, the total annual production of tailings in China was 16.49 billion tons, while the total utilization of tailings was only 312 million tons, with a comprehensive utilization rate of only 18.9% [7]. Western developed countries have started the comprehensive development and utilization of mineral resources since the first and middle of the 20th century and now have achieved waste-free and slag-free production in some mines [8]. China, on the other hand, started late, and the comprehensive utilization rate of tailings still has a big gap compared with European and American countries. Such a large number of tailings has serious safety hazards [9,10], which will not only pollute the environment and occupy land resources but also affect the healthy development of human society [11–13].

In response to this problem, the National Development and Reform Commission of China pointed out that it should make the best efforts to carry out the comprehensive utilization of resources and promote the green, efficient, high quality, high value, and large-scale utilization of solid waste. At present, the utilization of lead–zinc tailings in building materials provides the advantages of less pollution, high economic benefits, and sustainable development, and it is a highly promising and valuable method for the resource utilization of tailings [14]. Promoting the research and exploration of using lead–zinc tailings in building materials is of great significance to carry out comprehensive utilization of solid waste resources.

Thus, this paper summarizes the properties and hazards of lead–zinc tailings and discusses the feasibility and necessity of utilizing lead–zinc tailings in building materials. Then, the research progress of lead–zinc tailings in building materials is reviewed, focusing on the research status of lead–zinc tailings applied to cement, geopolymers, concrete, building bricks, and foam ceramics. Finally, the problems that lead–zinc tailings face in the development of building materials industry are analyzed, and its development prospects are forecasted, with a view to providing reference for the further utilization of lead–zinc tailings in the field of building materials.

2. Characteristics and Hazards of Lead–Zinc Tailings

2.1. Characteristics of Lead–Zinc Tailings

Lead–zinc tailings are a kind of composite minerals with a complex chemical composition [15–17]. There are obvious differences in the composition of lead–zinc tailings from different mines due to the differences in the beneficiation process, as shown in Table 1. However, there are also some similarities among these lead–zinc tailings in terms of composition; that is, the metal content is generally low, and the main compositions are oxides of Si, Al, Fe, Ca, and Mg [18,19]. The low content of valuable metals makes lead–zinc tailings lose some recovery value, but the high content of silica–alumina oxides gives them reuse value. By comparing the chemical composition of lead–zinc tailings with clay, it can be found that the composition of both is very similar, and the content of SiO_2, Fe_2O_3, and Al_2O_3 in some lead–zinc tailings is close to that in clay. In addition, the main minerals of lead–zinc tailings include quartz, feldspar, and clay, which are very close to natural sand minerals [3]. Therefore, lead–zinc tailings can be used as raw materials to produce cement or other construction materials in place of clay or sand. In summary, although the composition of lead–zinc tailings is complex and the valuable metals are difficult to recover, lead–zinc tailings still have high potential value in the production of building materials [20].

Table 1. Chemical composition of different lead–zinc tailings (wt.%).

References	Types	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	K_2O	LOI
Wang et al. (2017) [21]	Lead–zinc tailings	66.23	7.67	2.45	8.51	1.78	0.54	-	0.65	3.83
Zhang et al. (2015) [22]		69.92	10.41	1.89	2.19	1.39	0.51	0.55	2.17	3.68
Argane et al. (2015) [23]		68.44	9.380	2.200	1.99	0.48	0.7	0.449	5.46	-
Jankovic et al. (2017) [24]		43.26	11.11	15.57	20.01	4.31	0.92	0.32	1.00	5.61
Shen et al. (2013) [25]		49.43	17.23	8.23	5.88	9.02	0.41	1.43	4.59	-
Shen et al. (2013) [25]		26.97	5.17	4.36	33.84	15.48	0.16	0.55	1.57	9.53
Wei et al. (2021) [26]	Clay	61.37	14.32	4.74	12.40	2.36	1.03	0.03	2.59	-

2.2. Hazards of Lead–Zinc Tailings

Stockpiling in tailings reservoirs is currently the most direct disposal method for lead–zinc tailings. According to the Work Plan for Preventing and Resolving Safety Risks of Tailings Reservoirs in 2020, there are nearly 8000 tailings reservoirs in China, ranking first in the world [27]. A total of 64 types of minerals are involved, of which the minerals with the largest stockpile of tailings contain Zn and Pb [28]. These tailings reservoirs not only occupy a large amount of national land area but also have certain security risks [29,30], and they are also harmful to the environment [31–33], as shown in Figure 1. At present, most tailings reservoirs are a dangerous source with high potential energy formed by the accumulation of tailings, which are easily disturbed to form disasters such as debris flow, resulting in major casualties and property losses [34–36].

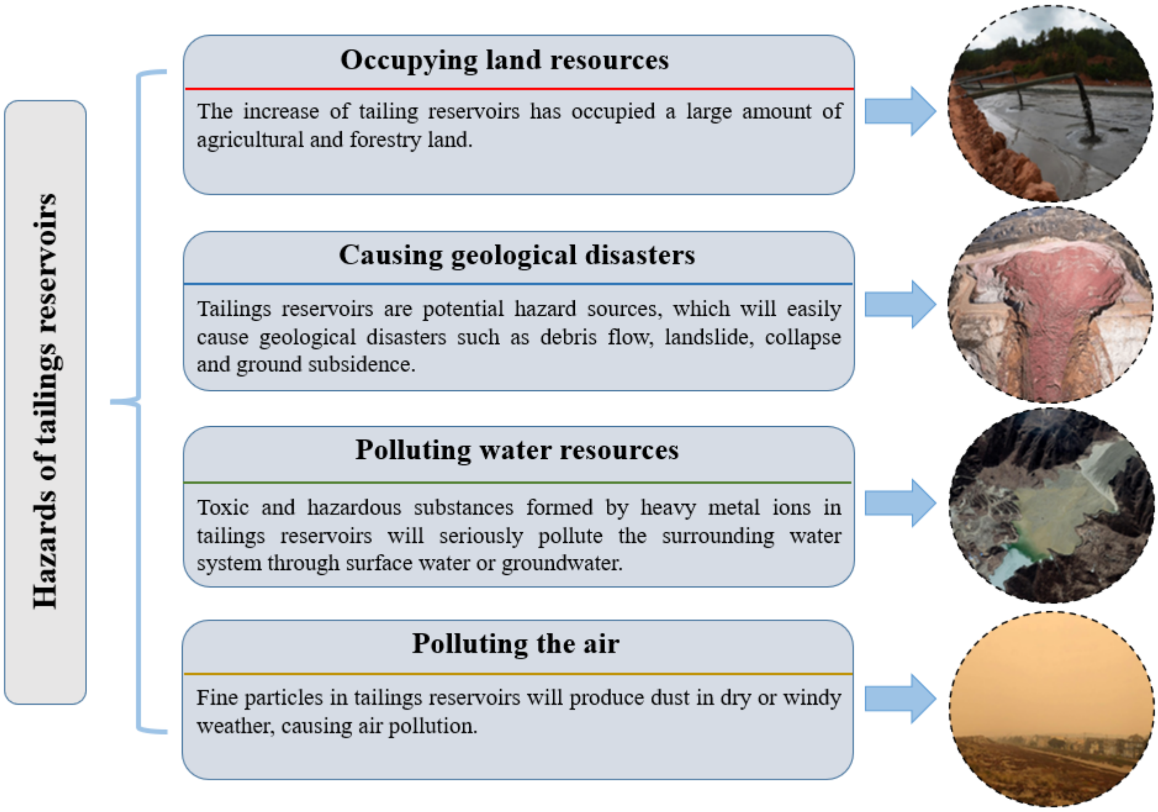

Figure 1. Adverse effects of tailings reservoirs on environment and human society.

In addition, the problem of environmental pollution caused by the stockpiling of lead–zinc tailings should not be underestimated [37–39]. Kan et al. [40] assessed the pollution of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn by analyzing their concentration data in lead–zinc tailings reservoirs in China and found that the average concentrations of all these heavy metals in soil have exceeded the corresponding background values [41]. Under the combined effect of internal and external factors, the lead–zinc tailings in the tailings reservoirs will leach out a large amount of heavy metal liquid [42], which will seriously pollute the water resources in the nearby area after infiltrating with rainwater. Mine soil is also the major carrier of heavy metal pollution [16,17]. The contaminated soil not only affects the growth of local plants and animals but also causes food safety and leads to the entry of heavy metal elements such as Pb, Zn, and Cd into people's bodies along the food chain [43]. Moreover, the large number of fine particles in tailings reservoirs can also cause serious dust pollution [44,45].

3. Utilization Ways of Lead–Zinc Tailings

In view of the fact that the various problems of tailings reservoirs are not conducive to the development of the mining industry, many countries have taken measures to reduce the impact of tailings stacking. The recycling of lead–zinc tailings has also been developed to a certain extent, and a preliminary resource utilization system has been formed, as shown in Figure 2. For tailings that still contain materials with recycling value, secondary recovery can be carried out through tailings reselection. Although tailings are waste, they may still contain some valuable metals and usable minerals due to the shortage of beneficiation technology. The key to achieving secondary recovery is to select a reasonable reselection process according to the characteristics of tailings, and the current development of new equipment and new technology provides a strong guarantee for the secondary recovery of tailings [46,47]. However, there are still technical difficulties in the recovery of some fractions in lead–zinc tailings [48]. Additionally, the secondary recovery still generates tailings, so it is not suitable as an effective method to consume a large number of tailings.

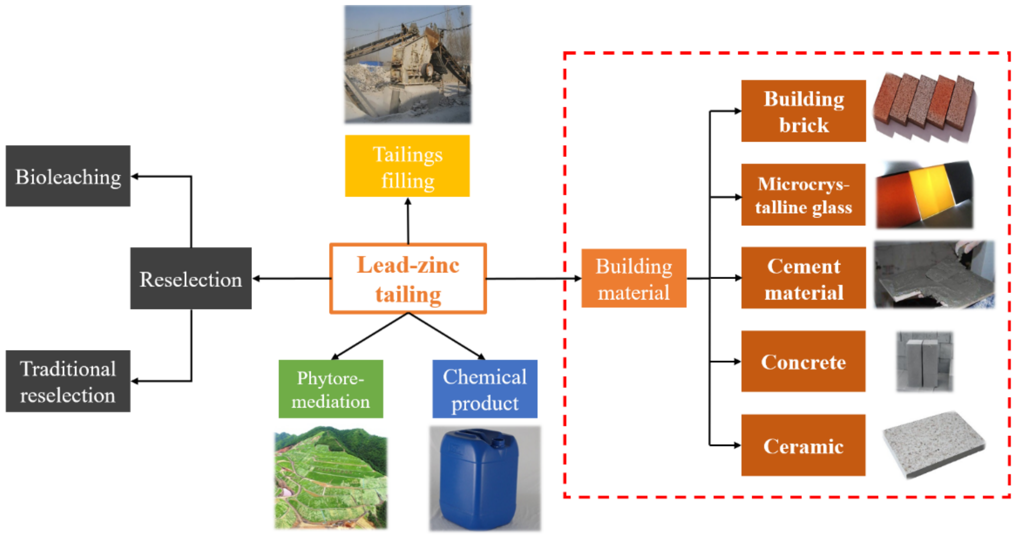

Figure 2. Utilization ways of lead–zinc tailings.

For tailings that no longer have reselection value, comprehensive utilization of them should be considered. At present, the diversified utilization of tailings carried out in western developed countries is mainly concentrated in mine filling material, road engineering paving material, concrete aggregate and mineral admixture, etc. [47]. However, the main applications in China are only two categories of mine filling material and building material [49]. However, the utilization of these two disposal methods of tailings accounts for about 53% and 43% of the total amount of tailings utilization in China, which already has a better application system. On the one hand, using tailings to fill mined-out areas can solve the problem of land resources occupied by tailings and avoid the occurrence of dangers such as ground collapse or landslides in mining areas [50,51]. On the other hand, because the main compositions of tailings are similar to building materials and their particle size distribution is suitable, making lead–zinc tailings into building materials is a more promising utilization method. These methods are helpful in treating large volumes of lead–zinc tailings. However, in order to prevent secondary pollution, it is necessary to make reliable assessments and prevent the possible pollutants released from the tailings [52,53].

4. Utilization of Lead–Zinc Tailings as Building Materials

The composition of lead–zinc tailings is very similar to that of building materials, light industrial materials, and inorganic chemical materials, and the elements such as Si and Al contained in lead–zinc tailings are also essential to produce building materials [54,55]. In recent years, many scholars have made studies on the use of lead–zinc tailings as raw materials to produce building materials and have achieved significant results in terms of the preparation process and raw material ratio. At present, lead–zinc tailings building materials research has been involved in the fields of cement, geopolymer, concrete, building brick, and foam ceramic.

4.1. Utilization of Lead–Zinc Tailings in Cement Production

Existing studies show that the utilization of various solid wastes in the cement industry is a very effective means. The main compositions of lead–zinc tailings are SiO_2, Al_2O_3, and Fe_2O_3, which can partially or totally replace the clay, iron, and aluminum raw materials in traditional cement raw materials. On the one hand, the addition of lead–zinc tailings can promote the production of tricalcium silicate (C_3S) in cement clinker. Additionally, the increased content of Pb and Zn is also conducive to the conversion of C_3S's crystal form from M3 to M1, which effectively improves the strength of the mixture [56]. The compressive strength of silicate cement clinker prepared by Chen et al. [57] using raw materials mixed with lead–zinc tailings reached 60.4 MPa after 28 days of curing, and the soundness met relevant standards. On the other hand, the addition of lead–zinc tailings can also improve the sinterability of the raw meal, decrease the heat absorption, and promote the burning of the clinker because of its mineralizer compositions and trace elements [58,59]. In the calcination of cement clinker, CaO reacts with acidic oxides to form minerals such as C_3S, C_2S, C_3A, and C_4AF. However, under the influence of the sinterability of the raw meal, there is still unreacted CaO in the clinker that exists in the free state (f-CaO), which has a direct negative impact on the quality and stability of cement [60]. However, mixing with lead–zinc tailings could effectively reduce the content of f-CaO in the clinker. As shown in Table 2, at a certain calcination temperature, the f-CaO mass fraction of the clinker with lead–zinc tailings was significantly reduced, while the flexural strength and the compressive strength were also improved to a certain extent, reaching the requirement of 42.5 ordinary portland cement. He et al. [61] also found the optimum mixing amount of lead–zinc tailings through the study of the sinterability of raw meal; when the amount of mixing was 12.25%, the content of f-CaO was the lowest, only 0.07%, and the state of minerals formation in clinker was good. However, the excessive mixing amount did not help to improve the sinterability of the raw meal and could not promote the formation of C_3S and the reduction of f-CaO in the clinker effectively.

Table 2. Performance comparison of cement clinker with different tailings content [60].

Sample	Mixing Amount of Tailings/%	f-CaO/%	Flexural Strength/MPa		Compressive Strength/MPa	
			3 d	28 d	3 d	28 d
S1	0	0.37	5.70	7.99	29.57	54.67
S2	15	0.10	6.51	8.21	27.08	47.90
S3	16	0.24	6.82	9.18	18.09	53.99
P.O 42.5	-		≥3.5	≥6.5	≥17.0	≥42.5

The utilization of lead–zinc tailings for cement preparation is beneficial in reducing tailings retention and saving resources, but there are still some limitations. The quality of the finished cement is determined by the chemical composition of the raw meal, which inevitably leads to strict requirements for the incorporation of lead–zinc tailings. Due to the differences in the composition of lead–zinc tailings from different sources, it is difficult to control the mechanical strength and workability of the finished cement to be stable and unchanged in the same production process. Additionally, it is necessary to pay attention to the potential pollution of lead–zinc tailings, where volatile heavy metals in lead–zinc tailings could pollute the environment along with flue gas emissions during the calcination process [62,63]. These have severely limited the application of lead–zinc tailings in cement production [64,65].

4.2. Utilization of Lead–Zinc Tailings in Geopolymer Production

Geopolymer is a kind of cementitious material similar to cement, and due to the special three-dimensional oxide network structure of inorganic polycondensation, geopolymer has better working properties, and the research on it has received attention from many scholars [66,67]. Compared with traditional silicate material, geopolymer has properties such as high-temperature resistance, high strength, high toughness, and corrosion resistance [68,69], and the production process is simpler and more environmentally friendly. It has great applications in the production of concrete, brick for building, backfill material, and porous material [70,71]. With the progress of studies, the silica–alumina raw materials for the preparation of geopolymers have been expanded to various industrial solid wastes containing active silica–alumina compositions [72,73]. Additionally, the application of lead–zinc tailings with high silica–alumina content for the preparation of geopolymers is also one of the research hotspots.

The properties of geopolymer are mainly determined by the reactivity of the precursor, which depends on the alkali solubility of silicon and aluminum in the raw material [74,75]. Some of the lead–zinc tailings are mainly composed of aluminates, silicates, and calcareous minerals, which are very similar to the raw materials needed for the preparation of geopolymer. Meanwhile, lead–zinc tailings also have a certain degree of alkali activity. The geopolymer prepared from lead–zinc tailings with high silica–alumina content and lead–zinc smelting slags had a dense microstructure and an excellent strength property [76], and the compressive strength at 28 days was up to 32.81 MPa. Therefore, this type of lead–zinc tailings can be directly used for the preparation of geopolymer materials [77]. As for lead–zinc tailings with low reactivity, they can be activated by mechanical milling or high-temperature treatment. Generally, the strength of the geopolymer prepared by using single lead–zinc tailings as raw materials is lower, and it is hard to meet the requirement for building materials. That is mostly attributed to the fact that the low activity components in lead–zinc tailings are not easily eroded by the alkalis, and it is difficult to form a more hydrated gel. However, this problem can be effectively avoided by mixing tailings and auxiliary materials such as metakaolin and mineral powder before preparing the geopolymer [78]. The addition of these active substances helps to increase the tailings reactivity, promote the geological polymerization reaction, and facilitate the development of geopolymer strength [79]. For example, the admixture of mineral powder could improve the activity of lead–zinc tailings and thus enhance the structural strength of the geopolymer, especially when the admixture is in the range of 5% to 20% with the best effect [80].

Furthermore, the geopolymer can also solidify heavy metal ions in lead–zinc tailings and reduce their threat to the environment [81,82]. The geopolymer solidifies heavy metal ions primarily by physical and chemical adsorption. The heavy metal ions not only physically adsorb with the geopolymer gel but also form chemical bonds with the aluminosilicate skeleton in it [83,84], and the solidification effect is remarkable. As shown in Figure 3, the curing rates of Zn^{2+}, Pb^{2+}, and Cd^{2+} in the geopolymer doped with lead–zinc tailings were all higher than 97.80%, and their leaching concentrations all fluctuated only within the limits, which were no longer at risk of contamination [85,86]. In addition, the heavy metals in the lead–zinc tailings have some optimization effect on the strength of the geopolymer; for example, the increase in Pb ion content in the geopolymer precursor can enhance its strength after molding [83,87].

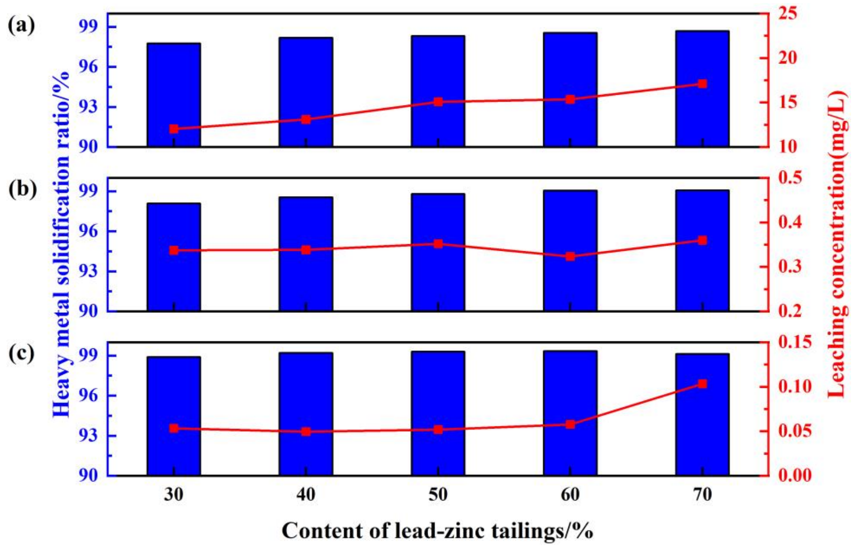

Figure 3. Solidification rate and leaching concentration of Zn^{2+} (**a**), Pb^{2+} (**b**), and Cd^{2+} (**c**) in geopolymers with different tailings contents [85].

However, most of the research on the geopolymer prepared from lead–zinc tailings is still at a primary stage, and the study of its polymerization mechanism is not clear and thorough enough, especially in the area of solidifying heavy metal ions and strength optimization, which needs to be studied thoroughly.

4.3. Utilization of Lead–Zinc Tailings as Concrete Admixture

In the field of construction, concrete is in great demand, and its production requires a large amount of sand and gravel minerals [88]. Uncontrolled mining of these minerals will undoubtedly cause disorders in the ecosystem. Fortunately, the silicate substances contained in lead–zinc tailings are necessary for the preparation of concrete. So, it is feasible to use lead–zinc tailings as admixtures for the preparation of concrete, which can not only improve the environment but also reduce the series of hazards generated by tailings accumulation [89,90]. There are two main studies on the utilization of lead–zinc tailings as concrete admixtures, one involves using them as cementitious materials in concrete [91], and the other involves using them as fine aggregates [92].

4.3.1. As Cementitious Materials

The chemical composition of lead–zinc tailings is composed mainly of oxides such as Al_2O_3, SiO_2, CaO, Fe_2O_3, and MgO, of which the content of SiO_2 can be up to 60%. Additionally, the fineness of the tailings is greatly improved by the secondary reselection, so there is a volcanic ash activity of lead–zinc tailings, which can be used as cementitious materials. However, the volcanic ash activity of lead–zinc tailings is much lower than that of cement, and mixing too much tailings in cement will make the strength too low. In order to meet the strength requirements, the admixture of lead–zinc tailings should not exceed 20% in general [20,93]. Therefore, it is necessary to improve the activity of lead–zinc tailings in order to increase their admixture as cementitious materials. Currently, mechanical activation is the most basic means to increase the activity of lead–zinc tailings [94]. Mechanical activation macroscopically increases the specific surface area of lead–zinc tailings and microscopically decreases their crystallinity. So, the contact area between the activated lead–zinc tailings and water is expanded, and the internal unstable structure is increased, which makes it easier for the volcanic ash reaction to occur. As shown in Figure 4, there is a significant increase stage in the compressive strength of the mortar test block prepared by mixing lead–zinc tailings after mechanical grinding [95,96]. However, with the increase in grinding time, the strength of the mortar test block showed a tendency to decrease instead [97,98]. It is because the grinding will make the individual particle size of lead–zinc tailings smaller and smaller, resulting in the adsorption of lead–zinc tailings particles into clusters with each other, and the particle size will be increased instead [95], as shown in Figure 5. At the same time, the lead–zinc tailings particles also adsorb highly active admixtures such as cement and fly ash, which ultimately leads to a reduction in the overall activity of the cementitious material [99]. Therefore, the grinding time of lead–zinc tailings should be reasonably controlled in the mechanical activation. The mixed grinding of various admixtures and the step grinding method can also be considered. Furthermore, thermal activation can also obviously improve the activity of lead–zinc tailings [100]. High temperatures can decompose carbonaceous minerals such as dolomite and calcite in the tailings and reduce their negative effect on the development of strength. As shown in Figure 6, due to the decomposition of the carbonaceous components, the structure of the particles is no longer compact but presents a loose and porous structure. That could promote the leaching of free $[SiO_4]^-$ and $[AlO_4]^-$ from the tailings, and thus the cementation activity of lead–zinc tailings could be improved [101]. However, the thermal activation treatment of lead–zinc tailings requires a large amount of heat consumption and has a low efficiency, which still needs more in-depth research.

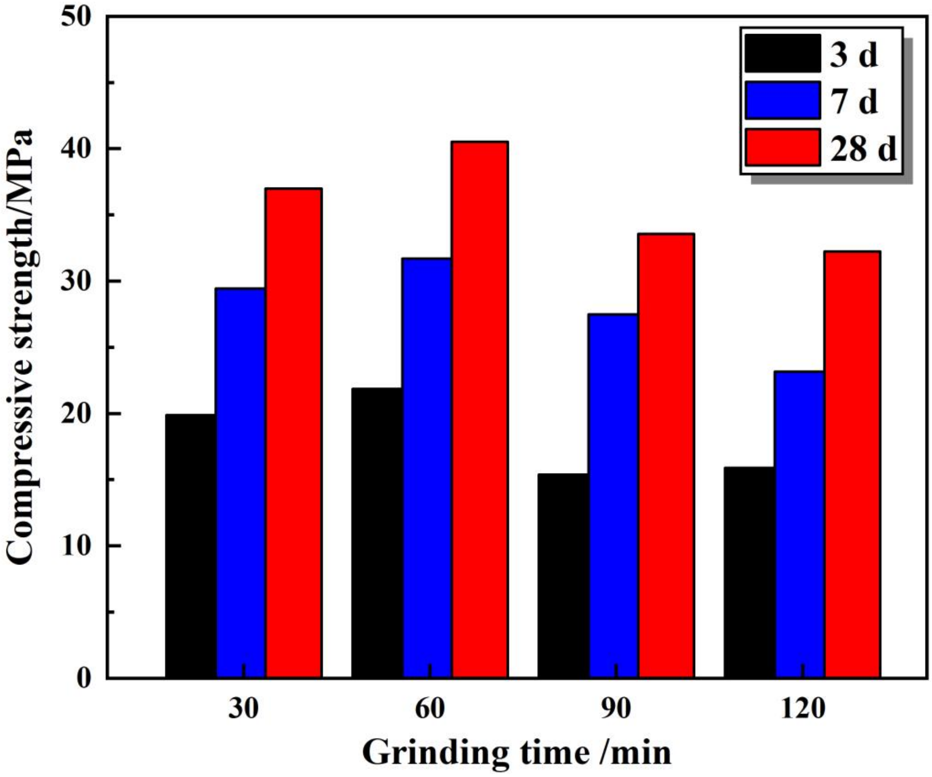

Figure 4. Relationship between grinding time of lead–zinc tailings and compressive strength of cement mortar [95].

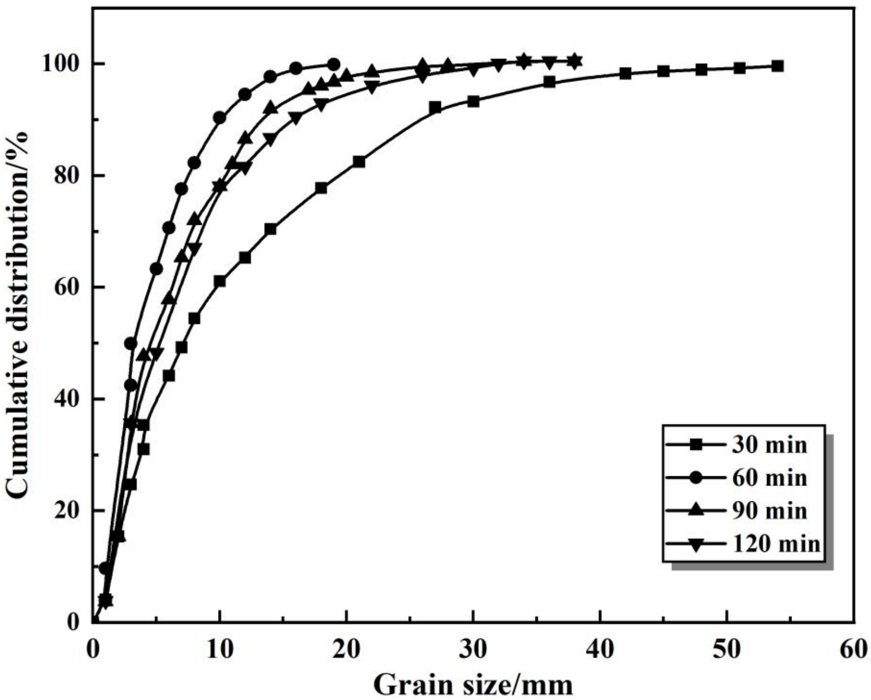

Figure 5. Relationship between grinding time and particle size of lead–zinc tailings [95].

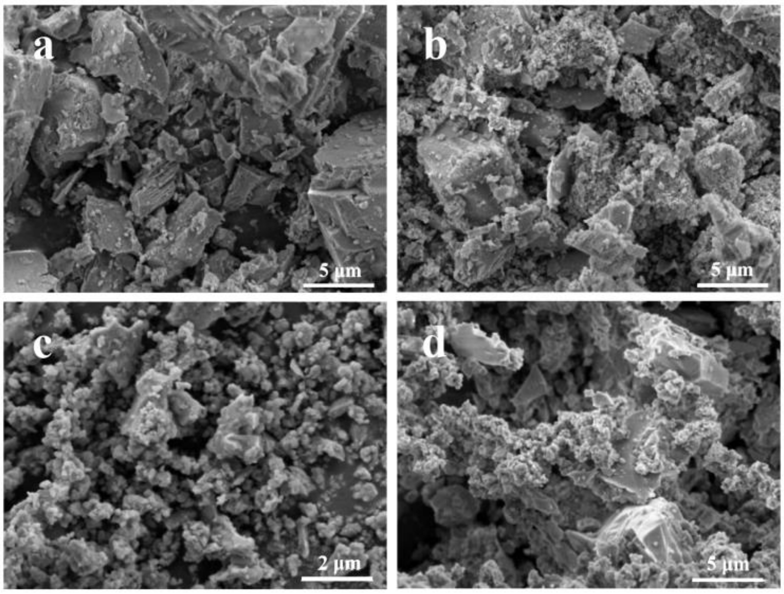

Figure 6. SEM photos of lead–zinc tailings after heat treatment at different temperatures [101]: (**a**) raw state; (**b**) 800 °C; (**c**) 1000 °C; (**d**) 1200 °C.

The active mineral components in lead–zinc tailings make dense cementitious structures inside the concrete through the "volcanic ash effect", while the microparticles not involved in the hydration reaction can also promote the improvement of concrete strength through the "micro-aggregate filling effect". During the hydration reaction, the excess microparticles are filled in the pore space between the cementitious particles and the aggregate. It can make the microstructure of concrete denser [102] and improve the skeleton strength. However, the "volcanic ash effect" of lead–zinc tailings is stronger than the "micro-aggregate filling effect". Mixing too much lead–zinc tailings may block the reaction pathway of active minerals, which in turn affects the generation and crystallization of hydration products [103], leading to the weakening of concrete strength. So, it is necessary to reasonably control the number of lead–zinc tailings incorporated as cementitious materials.

Presently, lead–zinc tailings have been able to be used as a partial replacement for cement in various concrete materials, especially in the field of ultra-high performance concrete (UHPC). Although UHPC has high strength and good durability, the demand for cement is huge, and this energy consumption can be effectively reduced by using lead–zinc tailings instead of cement. Lead–zinc tailings are less active than cement, but the use of lead–zinc tailings instead of 40% cement can still prepare UHPC with 28 days strength over 130 MPa [104]. In terms of workability, the admixture of lead–zinc tailings will reduce the fluidity of the concrete slurry. This is because the lead–zinc tailings particles are coarser, which increases the friction within the matrix and limits the free flow within the cementitious system [105]. However, it is found that the addition of lead–zinc tailings can significantly reduce the early autogenous shrinkage of concrete, as shown in Figure 7. On the one hand, this is because the crystal structure of lead–zinc tailings absorbs less water and delays the initial hydration phase [106]. On the other hand, due to the fact that the addition of lead–zinc tailings forms a stable skeleton structure, which can alleviate dry shrinkage [106]. In terms of chloride penetration resistance, the incorporation of lead–zinc tailings will weaken the chloride penetration resistance of concrete. The increased admixture of lead–zinc tailings decreases the integral activity of the cementitious material, leading to a decrease in the area distribution of C–S–H and the development of the concrete pore structure, which leads to an increase in chloride penetration [106]. However, despite this, the chloride permeability of the concrete prepared by replacing 40% of cement with lead–zinc tailings remained low and negligible, as shown in Figure 8. In conclusion, lead–zinc tailings do not seriously deplete the performance of concrete when used as cementitious materials, and heavy metal leaching tests have confirmed the environmental soundness of lead–zinc tailings concrete [107]. However, the mechanism of its influence on durability properties, such as anti-carbonation properties and frost resistance, still needs further confirmation.

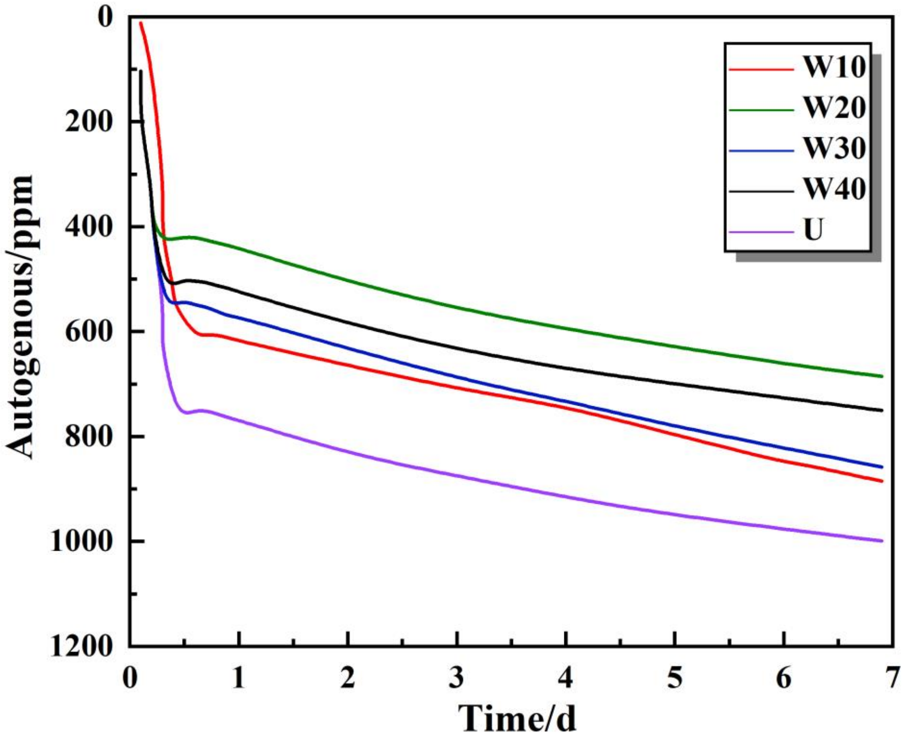

Figure 7. Autogenous shrinkage of UHPC with different contents of lead–zinc tailings [106].

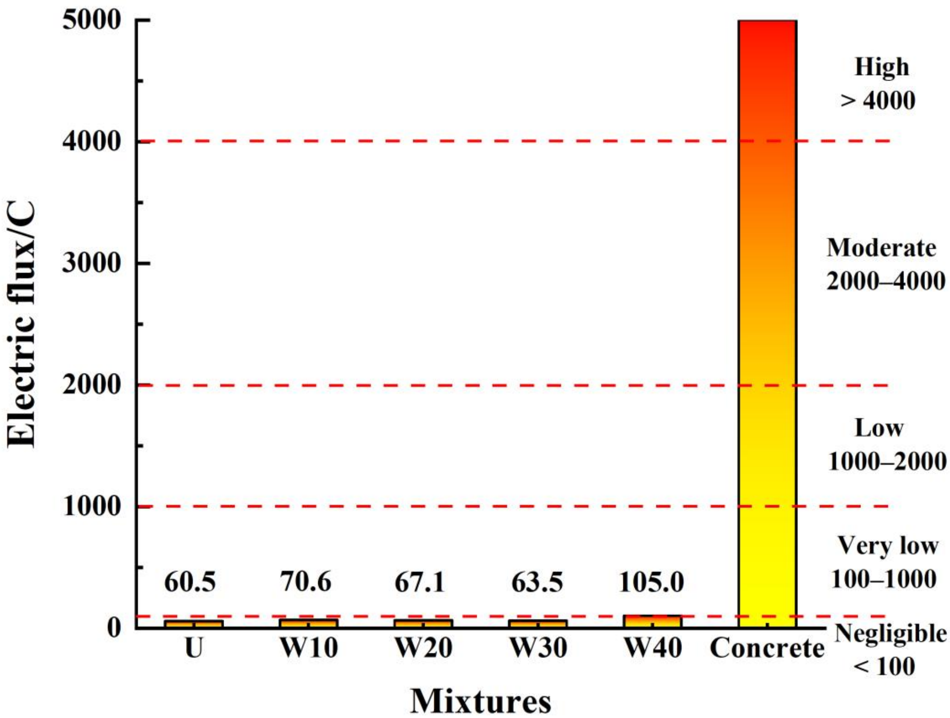

Figure 8. Effects of lead–zinc tailings content on the conductivity of UHPC [106].

4.3.2. As Fine Aggregate

Lead–zinc tailings contain a large number of quartz minerals with a similar particle size to natural sand, so they can be used as fine aggregate instead of river sand or mechanism sand in concrete. Lead–zinc tailings sand particles are poorly rounded, with a rougher surface and higher friction between each other, thus causing the concrete to become weak in fluidity and unfavorable to pumping. However, the angularity of lead–zinc tailings sand is beneficial to the stability of the internal skeleton of concrete, which in turn can inhibit shrinkage and promote the development of strength. As shown in Figure 9, the incorporation of lead–zinc tailings sand does not interfere with the development of concrete strength, and the compressive strength development trend of concrete mixed with lead–zinc tailings sand is consistent with that of ordinary concrete [108]. Meanwhile, due to the strong water absorption and water retention, the water inside the lead–zinc tailings sand will not participate in the hydration reaction prematurely. That will lead to a small actual water-cement ratio in the early stage of concrete and the phenomenon of high early strength [109]. However, when the amount of lead–zinc tailings sand is too much, the concrete strength will be significantly reduced because its particle strength is smaller than that of quartz sand. So, the incorporation amount of lead–zinc tailings sand should be reasonably controlled in practical application.

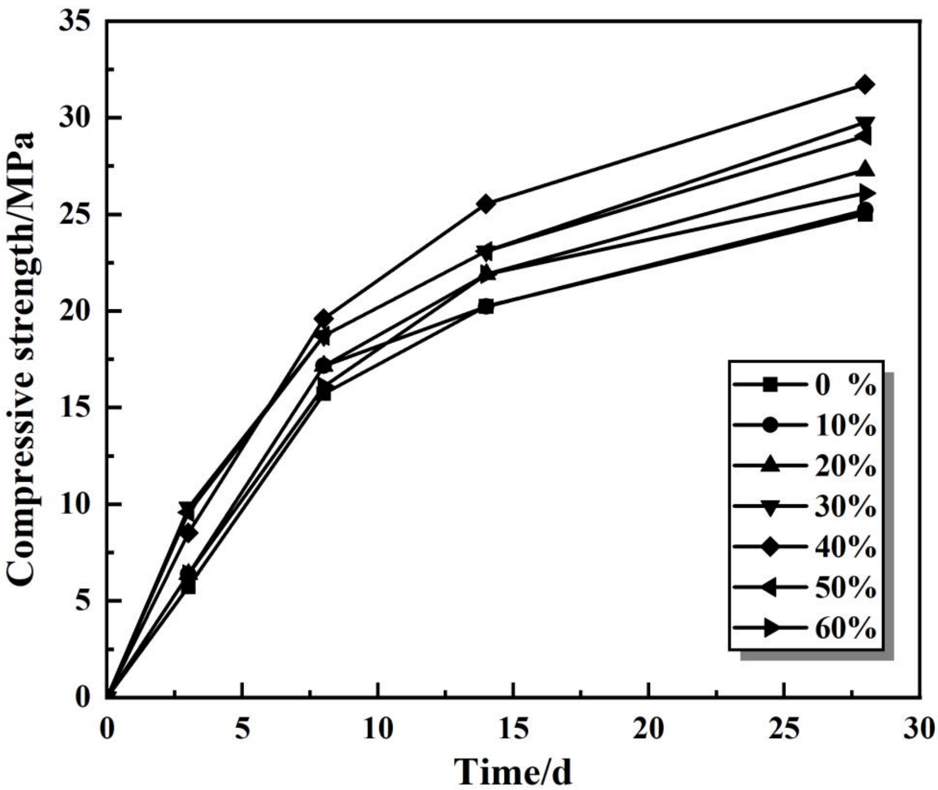

Figure 9. Compressive strength comparison of C25 concrete with different contents of lead–zinc tailings [108].

Besides, because of the high content of primary lead slag and barite, lead–zinc tailings sand also has a certain radiation protection ability and can be used to prepare radiation-proof concrete. It can be applied as a protective body in strong radiation fields such as medical and nuclear industries [110]. As shown in Figure 10, the absorption effect of lead–zinc tailings sand concrete on γ-rays is obvious, and the incorporation of lead–zinc tailings significantly improve the shielding performance of concrete. Compared with ordinary concrete, lead–zinc tailings sand concrete is thinner at the same shielding strength, which can effectively reduce space occupation. In addition, it is found that the higher the apparent density of lead–zinc tailings sand radiation-proof concrete, the stronger its shielding performance against γ-rays. Considering the shielding performance and strength performance together, the optimal admixture of lead–zinc tailings sand is as high as 40% to 60% [111].

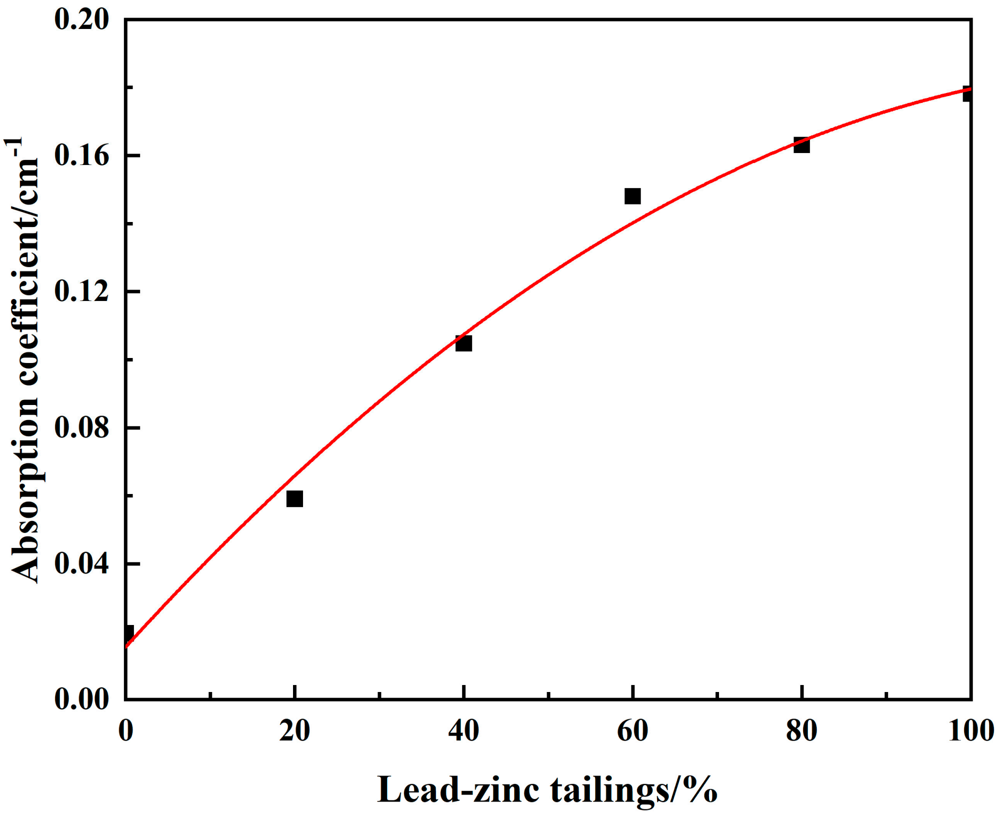

Figure 10. Relationship between γ-ray absorption coefficient of concrete and different contents of lead–zinc tailings [111].

4.4. Utilization of Lead–Zinc Tailings in Building Brick Production

As one of the most widely used building materials in the construction field, traditional building bricks consume a large amount of silica and calcium minerals, causing certain pressure on the natural environment. For this reason, the national policy of "no-clay" has been issued, and under the promotion of this policy, research on the production of building bricks from industrial solid waste such as tailings and slags has become more and more popular [112]. Since the composition of lead–zinc tailings is similar to that of raw materials for building bricks, the feasibility and effectiveness of brick-making from lead–zinc tailings have been explored. Lead–zinc tailings can replace clay in the preparation of sintered bricks. Additionally, the mineralizer component contained in lead–zinc tailings can widen the firing temperature range of sintered bricks and improve production efficiency. It has been shown that it is completely feasible to prepare sintered bricks by using lead–zinc tailings as raw material. Moreover, all types of indexes of such sintered bricks can meet the quality requirements of the building materials industry [113,114]. In addition, the effect of tailings sintered bricks on the fixation of heavy metals is also considerable. The leaching of Zn, Pb, Cd, and Cu from lead–zinc tailings can be effectively suppressed by controlling the ratio of various types of oxides in the raw material [115]. However, in actual production, sintered bricks have high energy consumption and require high equipment maintenance costs, which limit their development.

Lead–zinc tailings can also be used for the preparation of unfired bricks. Feng et al. [116] prepared lightweight unfired bricks using lead–zinc tailings as fine aggregate, and the compressive strength of the unfired bricks reached 9.3 MPa, which could be used as building filler blocks. Li et al. [117] also prepared unfired bricks with lead–zinc tailings as volcanic ash material, and the compressive strength of these unfired bricks could meet the MU20 requirement; that is, the average strength reached 20 MPa. All these studies obtained lead–zinc tailings unfired bricks with qualified properties. However, due to the lack of plasticity and volcanic ash activity of the lead–zinc tailings, a large amount of cement is still required in the preparation, which does not effectively increase the additive value. Therefore, it is possible to prepare geopolymer unfired bricks with better properties through geological polymerization. Moreover, the admixture of lead–zinc tailings in this method is up to 80%, which greatly improves the utilization efficiency [118] and deserves further study for promotion.

In summary, the utilization of lead–zinc tailings to prepare bricks for construction is possible to reduce resource loss and develop reuse value, but a systematic production model still must be created in order to reduce energy consumption and ensure that lead–zinc tailings can be used efficiently.

4.5. Utilization of Lead–Zinc Tailings in Foam Ceramic Production

Foam ceramic is a kind of green and energy-saving thermal insulation material with the advantages of light weight, sound insulation, high temperature resistance, corrosion resistance, and good compatibility with concrete materials, which is widely used in such industries as construction, national defense, and the chemical industry [119]. The point is that foam ceramic is also able to consume a large amount of industrial solid waste. At present, the use of lead–zinc tailings to prepare foam ceramics has achieved excellent results, and related research has become a hot spot. Some scholars successfully prepared foamed ceramic insulation panels with lead–zinc tailings and ceramic raw materials, in which the lead–zinc tailings were mixed with more than 50% [120]. During the sintering process of foamed ceramics, with the increase in sintering temperature, SiO_2 reacts with Na_2O and CaO to generate a glassy phase, which makes the internal mesh structure of foamed ceramics more developed and, thus, can enhance the mechanical properties of foamed ceramics [121]. Additionally, due to the easy generation of crystalline phases such as sodium feldspar with dense structure and good flexibility during the sintering process, the foamed ceramics have good chemical resistance [122].

Lead–zinc tailings can be used not only as raw materials for foam ceramics but also as foaming agents. The reaction of the internal composition of lead–zinc tailings has an obvious foaming effect [123], which has a significant influence on the pore structure of foam ceramics. The addition of lead–zinc tailings can change the ratio of reactants to make the ratio between CaO, Al_2O_3, and SiO_2 close to the composition of eutectic points in the ternary diagram of the CaO–Al_2O_3–SiO_2 system, thus accelerating the softening degree of ceramic raw materials [124]. As the sintering temperature increases, the viscosity of the liquid phase gradually decreases, and the bubble nuclei become larger and larger, eventually forming a porous structure, as shown in Figure 11 [124]. However, excessive lead–zinc tailings will lead to an increase in the softening temperature of the raw material, thus reducing the liquid phase content of the reactants during the sintering process and hindering the development of pores, as shown in Figure 11d. So, in the future, the impact of lead–zinc tailings on the performance of foam ceramics should be further quantitatively analyzed in order to provide some references for the reasonable control of the incorporation of lead–zinc tailings.

Increasing the sintering temperature is possible to improve the closed porosity, thermal conductivity, and mechanical properties of foam ceramics. However, too high a temperature may make the micropores expand and crack, resulting in an increase in volume and a decrease in density. That will lead to a decrease in the mechanical strength of the ceramics. Therefore, only reasonable control of the sintering temperature can effectively promote the formation of closed pores inside the foam ceramics. Liu et al. [125] found that the foam ceramics sintered at 970 °C had the most excellent properties, with higher porosity (76.2%), higher mechanical strength (5.3 MPa), and lower thermal conductivity (0.21 W/(m K)), which is expected to be applied in building insulation materials. However, at present, the properties and functions of lead–zinc tailings foam ceramics still need further specification to ensure that they can be promoted for applications in the construction field. Besides, lead–zinc tailings can also be used to prepare high-value fired materials such as ceramic granules [126] and microcrystalline glasses [127,128], which also have excellent properties.

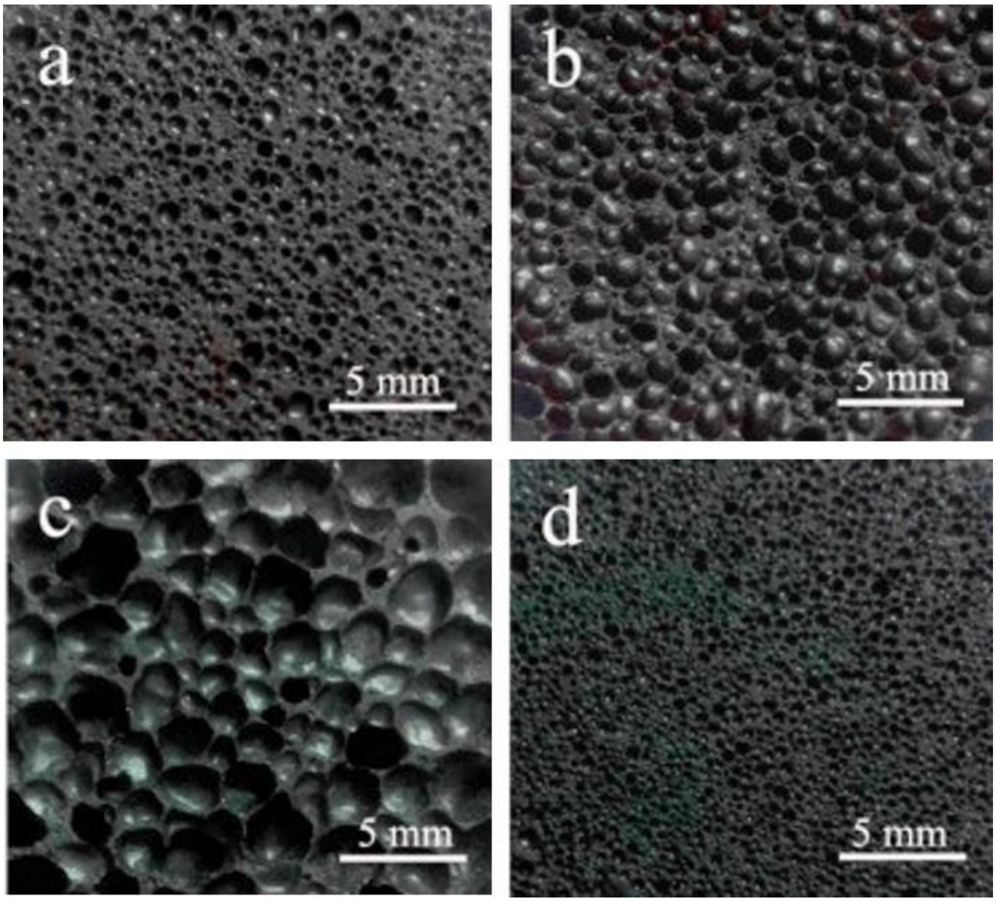

Figure 11. SEM photos of ceramics with different contents of lead–zinc tailings [124]: (**a**) 6 wt.%; (**b**) 12 wt.%; (**c**) 18 wt.%; (**d**) 24 wt.%.

5. Conclusions

As a typical representative of mine solid waste, lead–zinc tailings not only occupy a lot of land resources but also are not conducive to the protection of the natural environment. In fact, lead–zinc tailings are also a valuable secondary resource. The application of lead–zinc tailings as an admixture in the production of building materials can not only reduce the hazards caused by the stockpiling of tailings but also bring economic benefits. It is in line with the dual requirements of environmental protection and economic development. According to the available studies, lead–zinc tailings are mostly used in the preparation of traditional building materials such as cement, concrete, and construction bricks. Especially in the field of concrete, studies on the preparation of ultra-high-performance concrete with lead–zinc tailings are more popular. In addition, lead–zinc tailings can also be applied to prepare high-value building materials such as geopolymers, foam ceramics, and microcrystalline glass. They can utilize the potential value of lead–zinc tailings well and have great durability at the same time. However, it is still in the initial stage, and more in-depth experimental and theoretical studies are needed.

Presently, scholars have produced a lot of research on the application of lead–zinc tailings in building materials, but most of the substantial achievements are still in the laboratory stage. There is still some resistance to the improvement of various materials. The two main reasons are as follows:

(1) Influenced by the properties of mineral deposits and processing technology, the stability of lead–zinc tailings used as building materials in different regions is bound to be affected. This, in turn, leads to differences in product performance.
(2) In terms of product performance, most of the studies on building materials doped with lead–zinc tailings are still focused on the basic properties of materials, such as mechanical strength, while the research on durability, security, and workability is not thorough enough.

6. Prospects

As a result, it is necessary to continue future research deeply in order to accelerate the development of the utilization of lead–zinc tailings as building materials. First of all, the characteristics of lead–zinc tailings should be studied thoroughly. It is possible to construct a database of lead–zinc tailings and classify them according to the difference in physical and chemical properties. Secondly, the effect of lead–zinc tailings on the performance of building materials needs to be further explored. On the one hand, reducing the complexity of raw materials for building materials is necessary. On the other hand, the security and workability of existing lead–zinc tailings building materials should be improved. Finally, it is still important to explore new high-value utilization ways in order to expand the added value of lead–zinc tailings. In conclusion, the utilization of lead–zinc tailings as building materials has a broad development prospect and is a necessary direction for the future development of new economical materials. It will provide enough application space for the reuse of lead–zinc tailings.

Author Contributions: Conceptualization, H.L.; methodology, Z.Y.; software, R.L.; formal analysis, Z.Y.; investigation, R.L.; resources, H.L.; data curation, R.L.; writing—original draft preparation, R.L.; writing—review and editing, R.L., Z.Y. and H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hunan provincial key research and development Program (2022SK2082); Project (2021) of Study on Flood Disaster Prevention Model of Nanning Rail Transit; Projects (42277175) supported by National Natural Science Foundation of China; Project (NRMSSHR-2022-Z08) supported by Key Laboratory of Natural Resources Monitoring and Supervision in Southern Hilly Region, Ministry of Natural Resources.

Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there are no conflict of interest.

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