

# The possibility of using bottom ash from municipal solid waste incineration plants in Vietnam as road base material

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**Abstract:** *Recently, the Vietnamese Government has encouraged the use of advanced municipal solid waste (MSW) incineration technology for power generation, which is being increasingly applied. However, bottom ash generated from MSW incinerators is often discarded as waste and sent to landfills, resulting in a significant waste of resources. This paper presents the findings of a study conducted by the authors in 2023-2024 to assess the feasibility of using bottom ash from MSW incineration plants in Vietnam as road base material. Bottom ash samples were collected from the Xuan Son MSW Incineration Plant. Laboratory tests, conducted according to Vietnamese standards (TCVN) and ASTM guidelines, were used to evaluate the physical and mechanical properties of both the bottom ash and bottom ash-cement mixtures with cement content of 4%, 6% and 8%. The research results showed that the hazardous waste content in the bottom ash was below the allowable threshold specified in QCVN 07:2009. The particle composition of the bottom ash was classified as group A-1 according to AASHTO M145-91 (2004), which is considered suitable for subgrade construction. Furthermore, the mixture of bottom ash with 6% cement met the strength requirements for subbase layers of IV-VI grade roads, while the mixture with 8% cement satisfied the strength requirements for base layers of IV-VI grade roads.*

**Keywords:** *bottom ash-cement mixture, bottom ash after MSW incineration, base material, low-grade road, subbase material, Xuan Son MSW incineration plant.*

## 1. Introduction

Currently, Vietnam has 1,712 municipal solid waste (MSW) treatment facilities, including 467 MSW incinerators, 38 composting production lines, and 1,207 MSW landfills [10]. Of the total volume of collected MSW, approximately 70% (42,000 tons/day) is disposed of in landfills, 10% (6,000 tons/day) is processed at composting plants, and 20% (12,000 tons/day) is treated by incineration [25]. Recently, the Vietnamese Government has encouraged the use of advanced MSW incineration technology for power generation, which is being increasingly applied. However, bottom ash generated from MSW incinerators is often discarded as waste and sent to landfills, resulting in a significant waste of resources. At the same time, the ongoing expansion of infrastructure projects across the country is leading to a scarcity and rising costs of construction materials, particularly those used in road construction. Conducting research on the use of bottom ash from MSW incinerators as a road construction material will contribute to improving waste management solutions in Vietnam, providing an opportunity to recycle waste materials and reduce landfill use.

In the world, research conducted by [11] and [13] has indicated that bottom ash produced from MSW incinerator can be classified in a manner similar to soil classification. According to the Unified Soil Classification System (USCS), it is categorized as well-graded sand (SW), silty sand (SM), or poorly graded silty sand (SP-SM). In the AASHTO classification, it falls into Group A-1, which is recognized as a suitable material for subgrade construction. Additionally, a study by [1] revealed that the angular shape of bottom ash can complicate compaction efforts; however, it can achieve a compaction capacity of up to 90%. Compaction test results demonstrated that most bottom ash samples exhibit an optimal water content ranging from 12% to 18%, with a maximum dry density between 1,200 and 1,800 kg/m<sup>3</sup>. Studies conducted by [1], [8], [13] and [14] have examined the mechanical properties of bottom ash, revealing that its cohesion can reach up to 20 kPa. The elastic modulus is found to range from 35 to 90 MPa, while the dynamic elastic

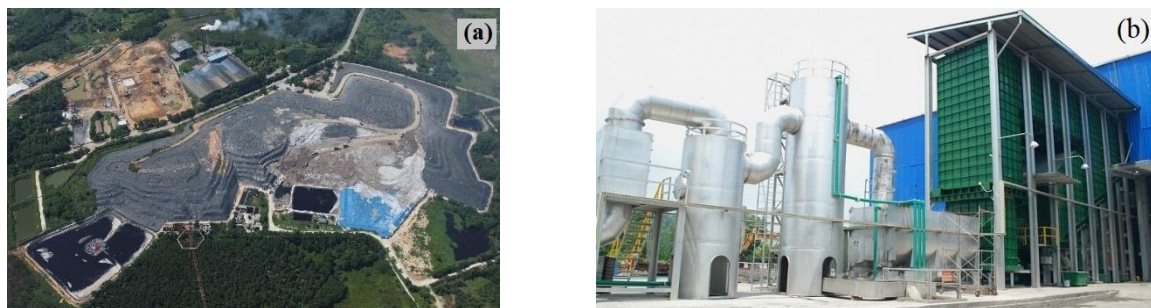
modulus varies between 50 and 150 MPa. These findings indicate that bottom ash generated from MSW incinerator can effectively be used as base and subbase materials, capping layer materials, and as an aggregate in cement concrete.

In Vietnam, research has primarily focused on the utilization of bottom and fly ash from thermal power plants in road construction. Studies by [3], [23], and [24] have indicated that bottom ash from these power plants meets the technical specifications required for roadbed materials. When mixed with additives and cement in varying proportions, this ash can be effectively used for subgrade, capping, subbase, and base layers. However, there has yet to be any research on the use of bottom ash from MSW incinerator as materials for road embankments and road bases.

This paper presents the findings of a study conducted by the authors in 2023-2024, investigating the feasibility of using bottom ash from the Xuan Son MSW Incineration Plant as low-grade road base materials.

### **Introduction to Xuan Son MSW Incineration Plant:**

The Xuan Son MSW Incineration Plant (Fig. 1), located in Xuan Son Commune, Son Tay Town, Hanoi, is managed and operated by Thanh Cong Cooperative. Construction began in August 2010 and was completed in January 2013 with an investment of VND 92 billion. The plant has a capacity of 250 tons of MSW per day and uses fixed grate/grid incinerator technology. MSW is first burned in the primary chamber at 900-1,100°C, producing bottom ash, exhaust gas, and incompletely burned dust. In the secondary chamber (1,000-1,300°C), these by-products undergo further burning, producing fly ash, CO<sub>2</sub>, and H<sub>2</sub>O. Oxygen levels are controlled to ensure slow, even burning, with 80% efficiency in MSW incineration and decomposition, leaving 20% inert waste. Ash typically makes up 5-7%.



**Fig. 1.** Xuan Son MSW Incineration Plant: a) Overall layout [28]; b) MSW incineration area [9]

## **2. Methods and materials**

### **2.1. Methods**

To investigate the feasibility of using bottom ash from MSW incinerators as low-grade road base materials, the authors collected bottom ash from the Xuan Son MSW Incineration Plant. Laboratory tests were conducted to determine the hazardous waste content and particle size distribution, assessing its potential as a construction material. The bottom ash was then mixed with cement in proportions of 4%, 6%, and 8%.

Samples of the bottom ash-cement mixture were cured for 7, 14, and 28 days, and basic mechanical properties were evaluated through laboratory tests, including compaction, California bearing ratio (CBR), unconfined compression, and splitting tensile strength, following Vietnamese standards (TCVN) and ASTM guidelines. The formation mechanism and strength development of the bottom ash-cement mixture were analyzed using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) tests.

Using Minitab 21 software, an ANOVA analysis of variance and post hoc analysis were performed to identify differences in compressive strength ( $R_n$ ) and splitting tensile strength ( $R_{ec}$ ) values according to Tukey's rule. The test results were compared with the material quality requirements specified in TCVN to evaluate the potential use of bottom ash from the Xuan Son MSW Incineration Plant as low-grade road base material.

### **Requirements for the quality of road base materials:**

The quality requirements for road base materials are specified in the following Vietnamese standards and regulations:

- Hazardous waste thresholds: Requirements are outlined in QCVN 07:2009/BTNMT [16].
- Road embankment materials: Quality requirements are detailed in AASHTO M145-1(2004) [2], and TCVN 9436:2012 [19].
- Road base materials: Quality standards are specified in TCVN 4054:2005 [15], TCVN 10379:2014 [20], and TCVN 8858:2023 [22].

These standards and regulations ensure that the materials used in road construction meet the necessary criteria for safety, durability, and environmental compliance.

## 2.2. Materials

To support the research, the authors collected three bottom ash samples from the Xuan Son MSW Incineration Plant. These samples were mixed with cement in proportions of 4%, 6%, and 8%. Subsequently, tests were conducted to determine the physical and mechanical properties of both the bottom ash samples and the bottom ash-cement mixtures at the laboratories of the University of Transport and Communications, the VNU University of Science (HUS), and the Institute of Foundations & Underground Construction (FECON INS) during the period of 2023-2024. The number of laboratory tests conducted is presented in Table 1.

**Tab. 1.** Number of laboratory tests conducted

No	Test	Property	Quantity
1	Synthetic chemical analysis using inductively coupled plasma mass spectrometry (ICP-MS), Ethos D microwave digestion	Content of hazardous waste in bottom ash	1 samp.
2	Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) tests	Microstructure, chemical and mineral composition of bottom ash	1 samp.
		Microstructure, chemical and mineral composition of bottom ash-cement mixtures after 7 and 28 days of curing	6 samp.
3	Particle size analysis, water content and specific gravity tests	Particle size distribution, water content and specific gravity of bottom ash	3 samp.
4	Compaction test	Optimum water content ( $W_{opt}$ ) and maximum dry unit weight ( $\gamma_{dmax}$ ) of bottom ash-cement mixtures with 0%, 4%, 6%, 8% cement content	4 samp. groups
5	California bearing ratio (CBR) test	CBR values of bottom ash-cement mixtures with 0%, 4%, 6%, 8% cement content	3 x 4 samp. groups
6	Unconfined compression test	Compressive strength ( $R_n$ ) of bottom ash-cement mixtures with 4%, 6%, and 8% cement content after 7, 14, and 28 days of curing	3 x 3 samp. groups
7	Splitting tensile strength test	Splitting tensile strength ( $R_{ec}$ ) of bottom ash-cement mixtures with 4%, 6%, and 8% cement content after 7, 14, and 28 days of	3 x 3 samp. groups

No	Test	Property	Quantity
		curing	

### 3. Research results

#### 3.1. Hazardous waste test results for bottom ash

The hazardous waste content in the bottom ash was determined through synthetic chemical analysis using ICP-MS, with sample digestion performed using the Ethos D microwave at the Institute of Chemistry, Vietnam Academy of Science and Technology (VAST). Test results provided by Thanh Cong Cooperative indicated that the hazardous waste content in the bottom ash was below the allowable thresholds specified in QCVN 07:2009 [16] (see Table 2). Therefore, bottom ash generated from MSW incineration can be used as a construction material.

**Tab. 2.** Analysis results of hazardous waste in the bottom ash

No.	Hazardous waste	Absolute content H (ppm)	Allowable threshold [H] (ppm) according to QCVN 07:2009/BTNMT	Evaluation
1	Arsenic (As)	23.56	40	Achieved
2	Barium (Ba)	48.32	2,000	Achieved
3	Silver (Ag)	2.94	100	Achieved
4	Cadmium (Cd)	0.67	10	Achieved
5	Lead (Pb)	150.24	300	Achieved
6	Cobalt (Co)	11.25	1,600	Achieved
7	Zinc (Zn)	2,860	5,000	Achieved
8	Nickel (Ni)	155.31	1,400	Achieved
9	Selenium (Se)	10.85	20	Achieved
10	Mercury (Hg)	0.11	4	Achieved
11	Chromium VI (Cr)	65.83	100	Achieved
12	Total cyanides (CN-)	18.09	590	Achieved

#### 3.2. Test results of physical properties of bottom ash

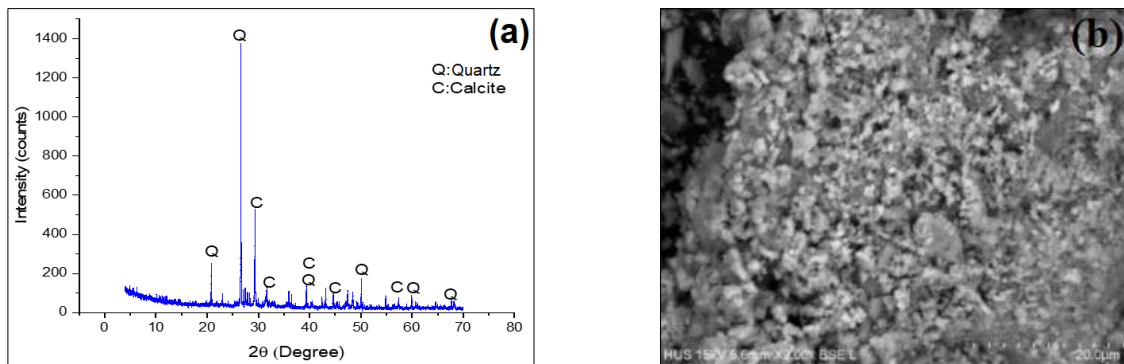
The physical properties of bottom ash (see Fig. 2a), including water content, specific gravity, and particle size distribution, were determined following ASTM D2216-19 [6], ASTM D854-23 [7], and ASTM D6913-17 (test method for particle-size distribution using sieve analysis) [4] standards at the University of Transport and Communications. The test results revealed that the bottom ash had a water content of 23.52%, a specific gravity of 2.64, and was classified as poorly graded sand. The composition included 23.1% gravel particles, 76.55% sand particles, and 0.35% silt particles (see Fig. 2b). According to AASHTO M145-91 (2004) [2], these bottom ash samples fall into Group A-1, indicating that they are suitable materials for subgrade construction.



**Fig. 2.** a) Bottom ash from the Xuan Son plant; b) Particle size distribution curve

### 3.3. Results of mineralogy, chemistry and microstructural testing of bottom ash

The mineralogy, chemistry, and microstructure of bottom ash were analyzed using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) at the University of Science (see Fig. 3). The XRD analysis indicated that the mineral composition of the bottom ash was predominantly quartz and calcite. The bottom ash samples contained the following oxides: SiO<sub>2</sub> (52.3%), Al<sub>2</sub>O<sub>3</sub> (8.5%), Fe<sub>2</sub>O<sub>3</sub> (3.4%), CaO (23.1%), MgO (2.2%), and K<sub>2</sub>O (2.4%). SEM analysis revealed that the bottom ash samples had a notably angular shape, which contributes to a large internal friction angle, thereby complicating the compaction process.



**Fig. 3.** a) XRD spectrum of bottom ash; b) SEM analysis of bottom ash

### 3.4. Test results of bottom ash-cement mixture

Bottom ash from the Xuan Son MSW Incineration Plant was mixed with Hoang Thach PCB40 cement in varying proportions: Sample 1 (M1) consisted of bottom ash with 0% cement; Sample 2 (M2) contained bottom ash with 4% cement; Sample 3 (M3) included bottom ash with 6% cement; and Sample 4 (M4) comprised bottom ash with 8% cement.

The basic mechanical properties of the bottom ash-cement mixtures were evaluated after 7, 14, and 28 days of curing through laboratory tests, including compaction, CBR, compressive strength, and splitting tensile strength, conducted at the University of Transport and Communications and the Institute of Foundations & Underground Construction. Additionally, SEM and XRD analyses were performed at the University of Science to investigate the strength formation mechanisms of the bottom ash-cement mixtures. The number of each test is summarized in Table 1.

#### Results of compaction test for bottom ash-cement mixture:

The optimum water content ( $W_{opt}$ ) and maximum dry unit weight ( $\gamma_{d\ max}$ ) of sample groups M1, M2 and M3 after 7, 14 and 28 days of curing were determined through compaction test according to TCVN 12790:2020 [20]. Each group consisted of 3 samples. The test results indicated that  $\gamma_{d\ max}$  values ranged from 16.29 kN/m<sup>3</sup> to 16.60 kN/m<sup>3</sup>, while  $W_{opt}$  values of the mixtures ranged from 16.62% to 14.67%. Notably,

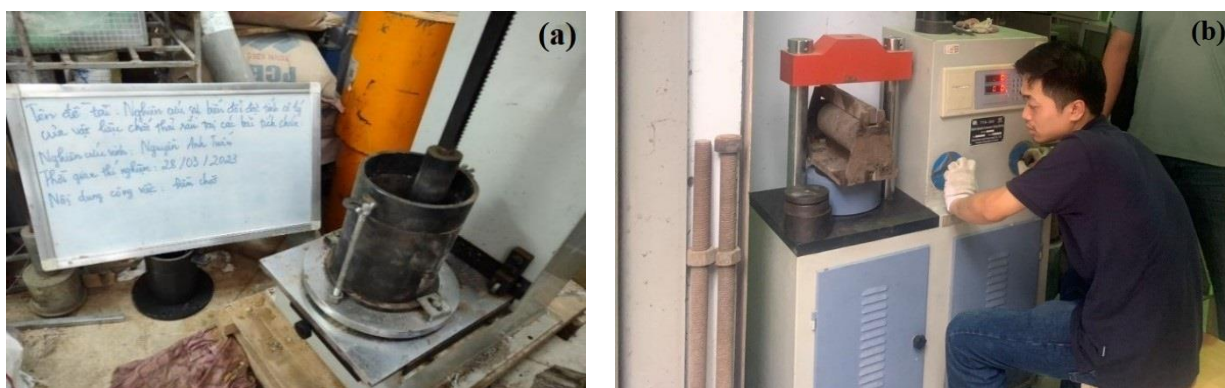
the  $\gamma_{dmax}$  value of the bottom ash-cement mixtures showed only a slight increase of about 2% compared to the bottom ash sample without cement.

**Tab. 3.** Results of compaction test for bottom ash-cement mixtures

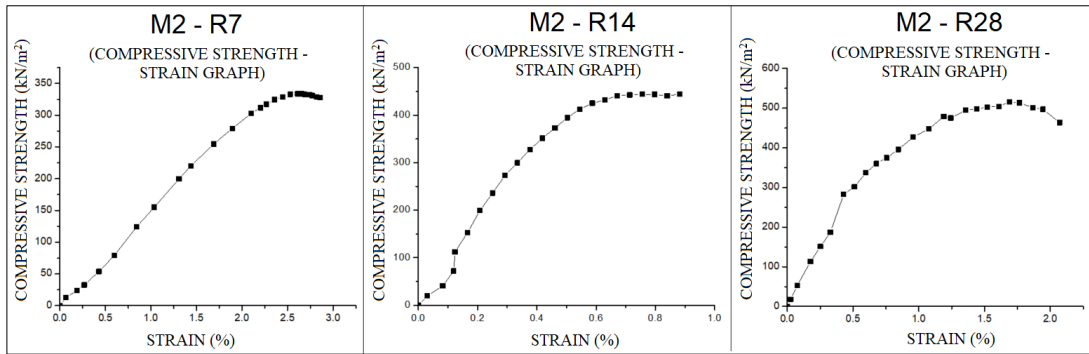
No.	Cement content (%)	Sample group No.	Property	
			$\gamma_{dmax}$ (kN/m <sup>3</sup> )	W <sub>opt</sub> (%)
1	0	M1	16.29	16.62
2	4	M2	16.38	16.37
3	6	M3	16.46	15.81
4	8	M4	16.60	14.67

**Test results of compressive strength ( $R_n$ ) and splitting tensile strength ( $R_{ec}$ ) of bottom ash-cement mixtures:**

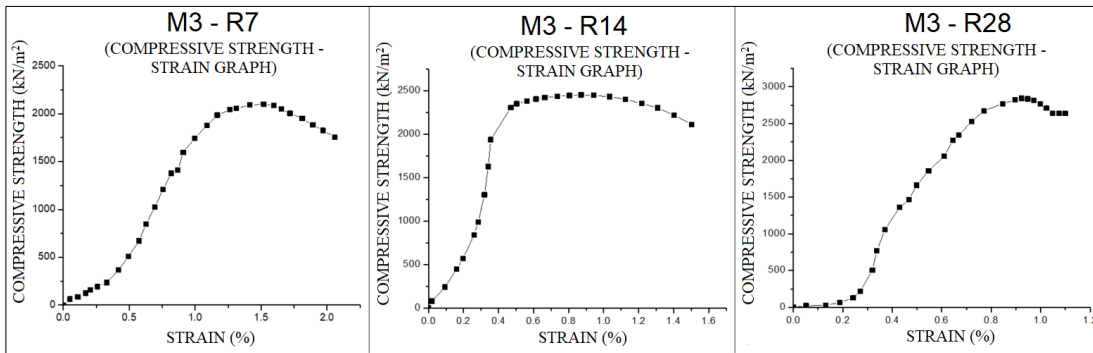
After conducting the compaction tests, sample groups M2, M3, and M4, corresponding to the optimal water content and maximum dry unit weight, were cast into standard samples and regularly maintained. The samples were then cured for 7, 14, and 28 days, after which they were immersed in water for 72 hours before undergoing unconfined compression tests according to ASTM D1633-17 [5] and splitting tensile tests in accordance with TCVN 8862:2011 [17] (see Fig. 4). Each group comprised three samples. The results of the compression and splitting tensile tests are summarized in Table 4 and illustrated in Figures 5 to 7. The test results indicated that both compressive strength ( $R_n$ ) and splitting tensile strength ( $R_{ec}$ ) of the bottom ash-cement mixtures increased with curing age and cement content. From Figures 5 to 8, it is evident that the cement content has the most significant impact on the strengths of the bottom ash-cement mixtures. A 6% cement content notably affects the strengths. The strength values of the mixtures increased rapidly with a 6% cement content, particularly after 14 days of curing. Notably, samples M3 and M4 met the strength requirements for cement-reinforced soil materials as specified in TCVN 10379:2014 [19] and TCVN 8858:2023 [22]. The bottom ash-cement mixture with 6% cement (M3) satisfied the strength requirements for the subbase layer of IV-VI grade roads, with  $R_n$  exceeding 1.5 MPa after 28 days of curing. Similarly, the bottom ash-cement mixture with 8% cement (M4) met the strength requirements for the base layer of IV-VI grade roads, with  $R_n$  greater than 3 MPa and  $R_{ec}$  exceeding 0.35 MPa after 28 days of curing.



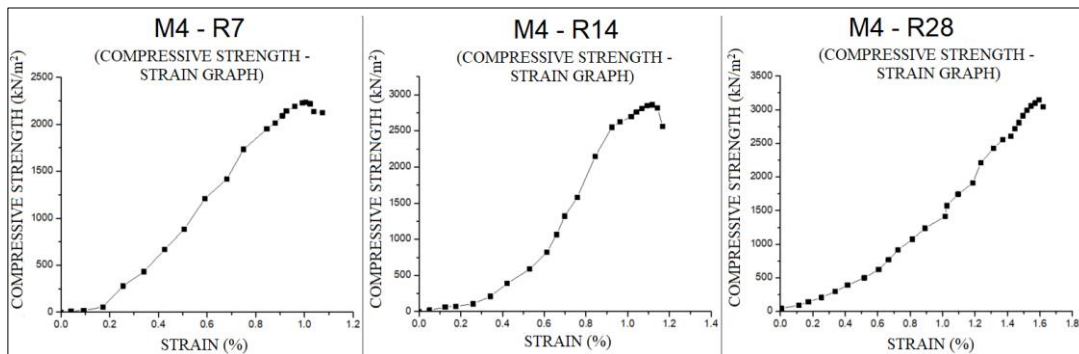
**Fig. 4.** a) Sample preparation; b) Performance of bottom ash-cement mixture in splitting tensile test



**Fig. 5.** Relationship between compressive strength ( $R_n$ ) and strain of M2 sample after 7, 14, 28 days of curing



**Fig. 6.** Relationship between compressive strength ( $R_n$ ) and strain of M3 sample after 7, 14, 28 days of curing

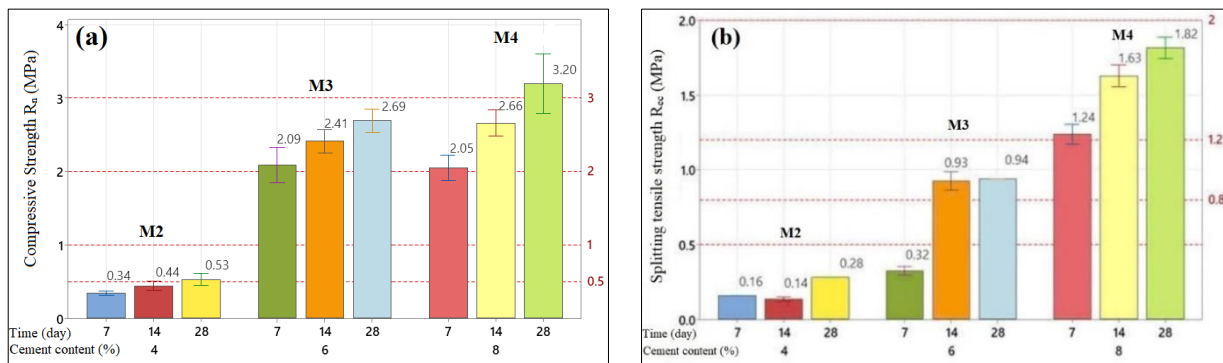


**Fig. 7.** Relationship between compressive strength ( $R_n$ ) and strain of M4 sample after 7, 14, 28 days of curing

**Tab. 4.** Results of compression and splitting tensile tests for bottom ash - cement mixtures

No.	Sample group No.	X (cement content, %)	T (age, day)	$R_n$ (MPa)	$R_{ec}$ (MPa)
1	M2-1	4	7	0.33	0.16
2		4	14	0.44	0.14
3		4	28	0.49	0.28
4	M3-1	6	7	2.01	0.33
5		6	14	2.34	0.93
6		6	28	2.72	0.94

No.	Sample group No.	X (cement content, %)	T (age, day)	R <sub>n</sub> (MPa)	R <sub>ec</sub> (MPa)
7	M4-1	8	7	2.13	1.26
8		8	14	2.74	1.60
9		8	28	3.01	1.80
10	M2-2	4	7	0.35	0.16
11		4	14	0.47	0.14
12		4	28	0.55	0.28
13	M3-2	6	7	2.20	0.33
14		6	14	2.44	0.95
15		6	28	2.62	0.94
16	M4-2	8	7	2.00	1.21
17		8	14	2.60	1.66
18		8	28	3.31	1.80
19	M2-3	4	7	0.35	0.16
20		4	14	0.42	0.13
21		4	28	0.55	0.28
22	M3-3	6	7	2.07	0.31
23		6	14	2.46	0.90
24		6	28	2.74	0.94
25	M4-3	8	7	2.02	1.25
26		8	14	2.64	1.63
27		8	28	3.27	1.85



**Fig. 8.** R<sub>n</sub> (8a) and R<sub>ec</sub> (8b) graph of bottom ash-cement mixtures with 4%, 6%, 8% cement content over time according to ANOVA analysis using Minitab 21 software

Using Minitab 21 software, ANOVA analysis of variance and post hoc analysis were conducted to detect differences in values according to Tukey's rule for compressive strength (R<sub>n</sub>) and splitting tensile strength (R<sub>ec</sub>). The results indicated that the test results for both R<sub>n</sub> and R<sub>ec</sub> were highly reliable (see Fig. 8).

The regression analysis performed using Minitab 21 yielded the following regression equation for R<sub>n</sub> and R<sub>ec</sub>:

Regression equation for R<sub>n</sub>:

$$R_n = -8.389 + 2.959 * XM + 0.0109 * T - 0.21569 * XM * XM - 0.001311 * T * T + 0.01094 * XM * T \text{ (MPa)}$$

(1)

Regression equation for  $R_{ec}$ :

$$R_{ec} = -0.287 - 0.177 \cdot XM + 0.0556 \cdot T + 0.0368 \cdot XM \cdot XM - 0.00181 \cdot T \cdot T + 0.00477 \cdot XM \cdot T \text{ (MPa)}$$

(2)

where:

T is curing time (7, 14, 28 days of curing);

XM is cement content (4%, 6%, 8%).

Model summary for $R_n$			Model summary for $R_{ec}$		
S	$R_{-sq}$	$R_{-sq(adj)}$	S	$R_{-sq}$	$R_{-sq(adj)}$
0.085037	99.47%	99.35%	0.109794	97.44%	96.83%

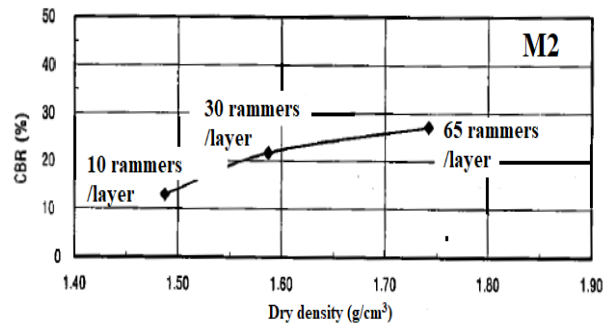
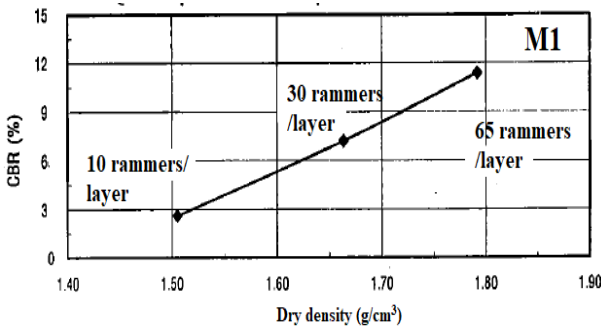
Note: S is the total sum of squares;  $R_{-sq}$  is the coefficient of determination;  $R_{-sq(adj)}$  is the adjusted coefficient of determination.

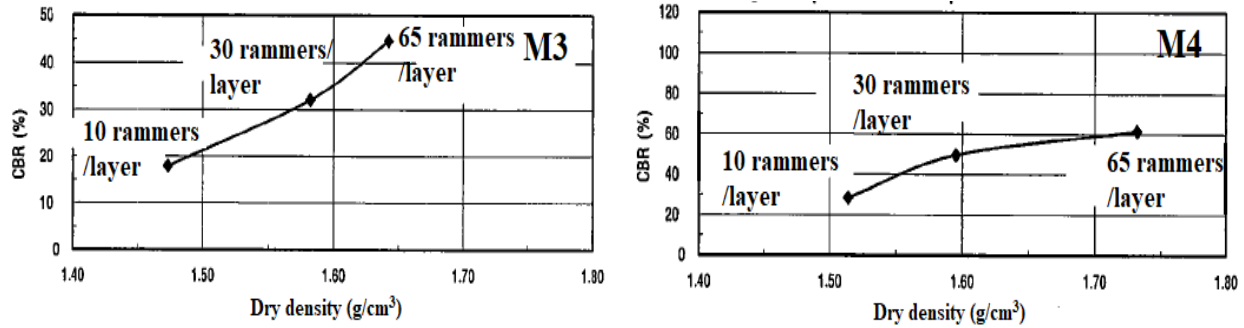
The  $R_{-sq(adj)}$  for the  $R_n$  model is 99.35%, while that for  $R_{ec}$  model is 96.83%. These high values indicate that equations 1 and 2 possess a strong reliability.

**CBR test results of bottom ash-cement mixtures:**

Sample groups M1, M2, M3, and M4 were compacted to create CBR samples, with each group consisting of three samples. The natural water content of the samples was measured, and the appropriate amount of water was added to achieve the calculated optimal water content. The samples were then compacted in CBR molds, with specified compaction levels of 10 rammers/layer, 30 rammers/layer, and 65 rammers/layer. After compaction, the water content and dry density of the samples were determined.

Following compaction, the samples were immersed in water for 96 hours, and their swelling after immersion was measured. The CBR test was conducted according to TCVN 12792:2020 [21]. The relationship between the CBR value and dry density of the samples in each group is illustrated in Fig. 9. The test results, presented in Table 5, indicate that the CBR value of the samples increased significantly with higher cement content. Notably, all samples exhibited no swelling after immersion in water and had CBR values that met the requirements specified in TCVN 9436:2012 [18], where the minimum allowable CBR value is 6%.





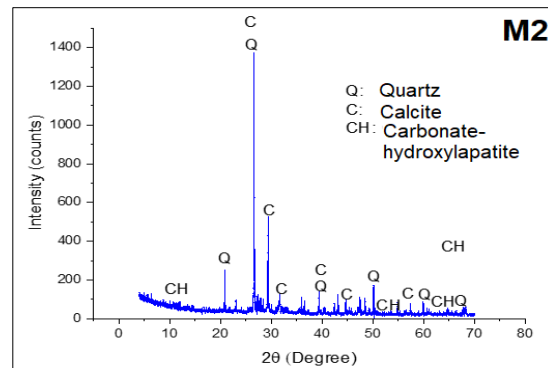
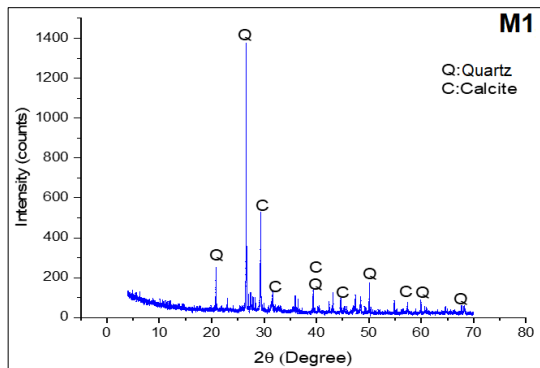
**Fig. 9.** Relationship between dry density and CBR value

**Tab. 5.** Laboratory CBR test results

No.	Cement content (%)	Sample group No.	CBR (%) corresponding to the compaction coefficient K		
			K = 1.00	K = 0.98	K = 0.95
1	0	M1	4.44	3.54	2.24
2	4	M2	21.23	18.86	14.40
3	6	M3	33.55	28.05	21.52
4	8	M4	51.81	45.24	32.26

**XRD and SEM analysis results:**

The XRD analysis results for the bottom ash-cement mixtures with 0%, 4%, 6%, and 8% cement content are presented in Figures 10 and 11. Initially, the bottom ash contained primarily calcite (CaCO<sub>3</sub>) at 42.7% and quartz (SiO<sub>2</sub>) at 57.3% (see Fig. 10). Following the mixing of bottom ash with cement, a new mineral phase, Carbonate-hydroxylapatite (Ca<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub>), was observed (Figs. 10 and 11). This formation is attributed to hydration process of the cement.



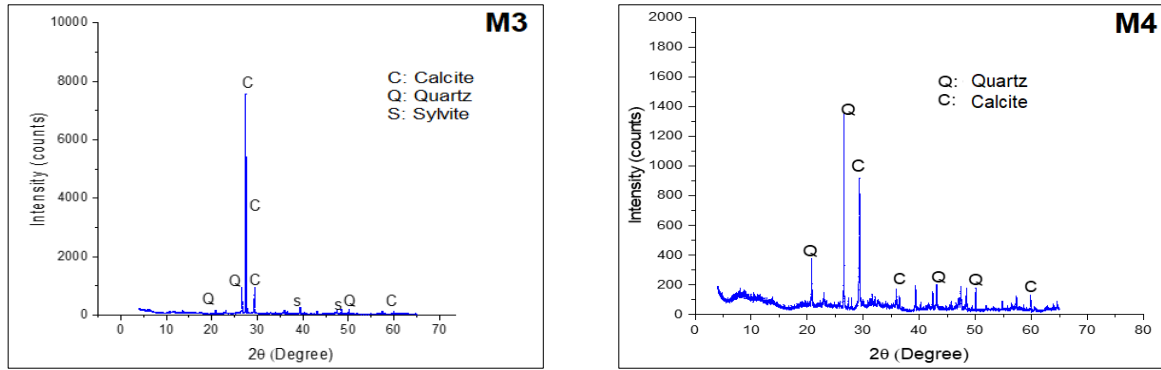


Fig. 10. XRD diagram of bottom ash-cement mixtures after 14 days of curing

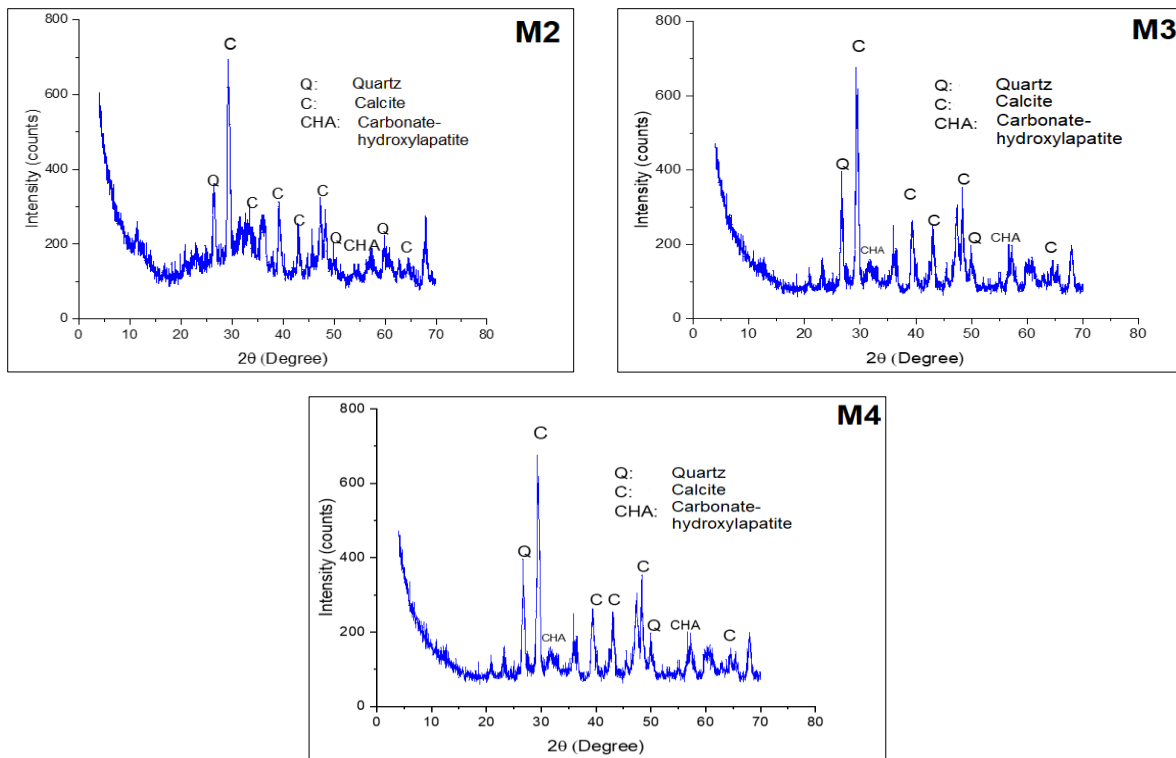
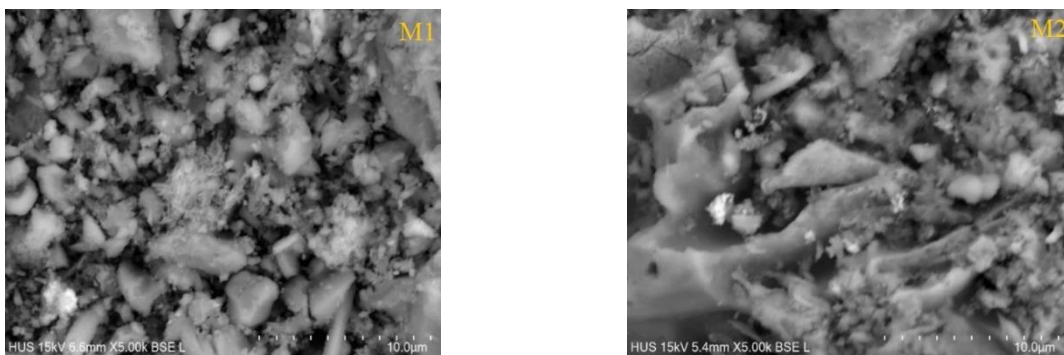
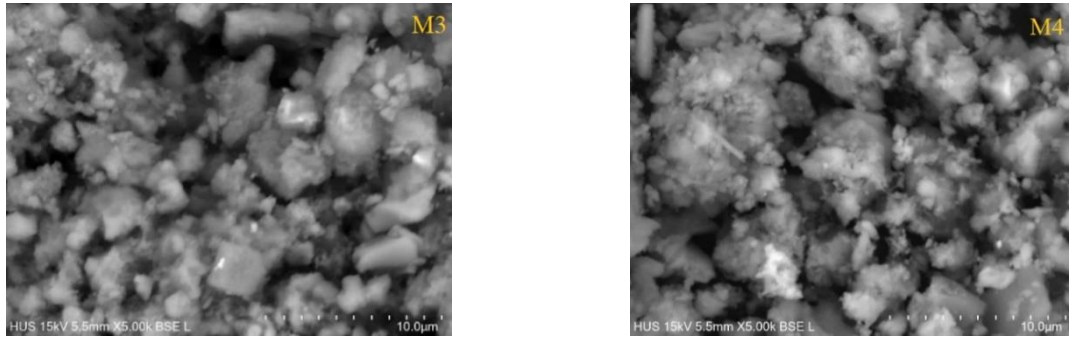
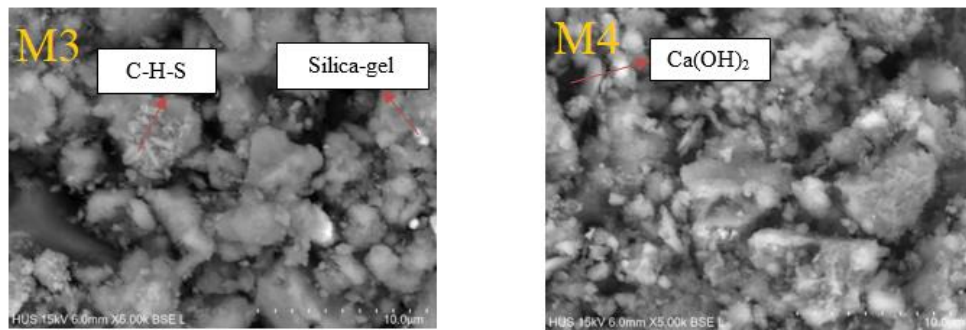


Fig. 11. XRD diagram of bottom ash-cement mixtures after 28 days of curing





**Fig. 12.** SEM analysis results of bottom ash-cement mixtures after 14 days of curing

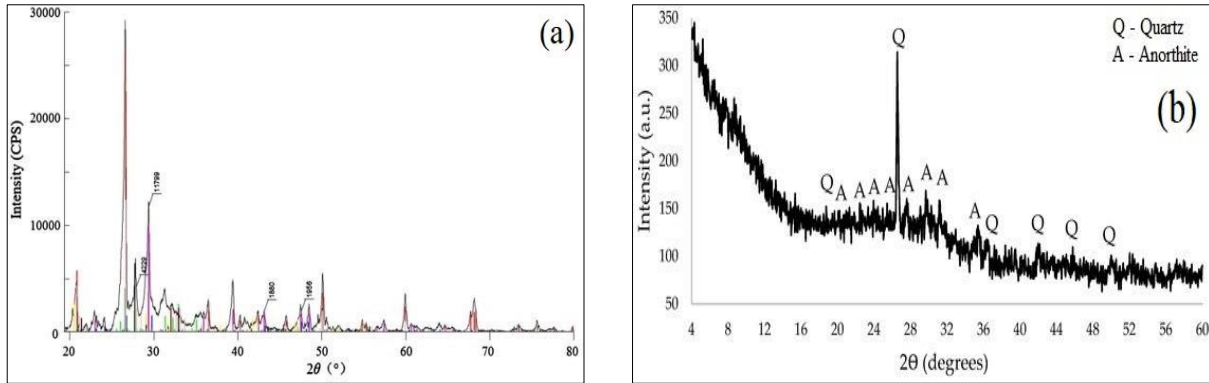


**Fig. 13.** SEM analysis results of bottom ash-cement mixtures after 28 days of curing

The results of the SEM analysis are illustrated in Figures 12 and 13. The initial composition of bottom ash consists of  $\text{CaCO}_3$  and  $\text{SiO}_2$ . Upon mixing with cement and water, hydration and pozzolanic reactions take place, leading to the formation of new minerals, including Carbonate-hydroxylapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ), Calcium hydroxide silicate (C-S-H), Silica gel ( $\text{SiO}_2$ ), and Calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ). These new phases condense and harden, which reduces porosity, increases strength, and decreases permeability in the bottom ash-cement mixtures.

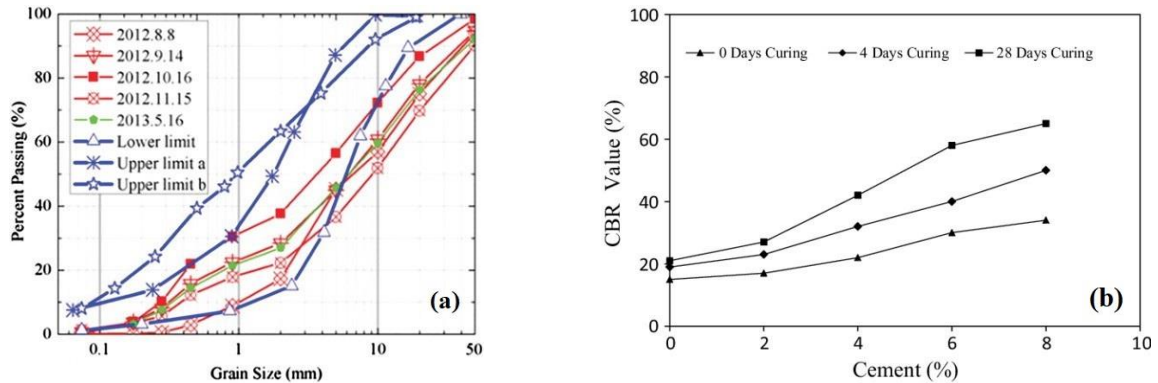
#### 4. Discussion

Compared to the findings of [12] and [29] observed that the concentrations of  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{MgO}$  in bottom ash after MSW incineration at the Xuan Son Plant were higher than those reported in other countries (see Fig. 14). This discrepancy can be attributed to the suboptimal classification of MSW in Vietnam, where the waste entering the incinerators still contains a significant amount of inorganic materials. Additionally, the composition of bottom ash is influenced by factors such as incineration temperature and technology.



**Fig. 14.** XRD analysis results of bottom ash after MSW incineration in Taizhou city, China (Fig. 14a) [29] and in Klaipeda region, Lithuania (Fig. 14b) [12]

The hazardous waste content, particle composition, optimal water content, maximum dry unit weight, and CBR value of bottom ash from the Xuan Son MSW Incineration Plant align with global research findings (see Fig. 15).



**Fig. 15.** a) Particle size distribution of bottom ash from MSW incineration plants worldwide [26]; b) Relationship between CBR and cement content of the bottom ash-cement mixture in Chandigarh, India [27]

### 5. Conclusion

The research results on the potential use of bottom ash from the Xuan Son MSW Incineration Plant as road base material indicated the following:

1. The hazardous waste content in the bottom ash from the Xuan Son plant was below the allowable threshold specified in QCVN 07:2009, confirming its suitability as a construction material.
2. The particle composition of the bottom ash consists of 23.1% gravel particles, 76.55% sand particles, and 0.35% silt particles, classifying it as poorly graded sand with gravel. According to AASHTO classification, it falls into group A-1, which is considered a good material for subgrade construction.
3. The compressive strength ( $R_n$ ), splitting tensile strength ( $R_{ec}$ ), and California bearing ratio (CBR) of the bottom ash-cement mixtures increase with age and cement content. Specifically, the bottom ash with 6% cement met the strength requirements for the subbase layer of IV-VI grade roads, while the mixture with 8% cement met the requirements for the base layer of IV-VI grade roads.
4. The physical and mechanical properties of bottom ash and its cement mixtures show consistency with findings from other studies conducted globally.

5. Due to budget and time constraints, this research was limited to bottom ash samples obtained from the Xuan Son MSW Incineration Plant. To gather more comprehensive and diverse data, further studies are necessary at MSW incineration plants employing various incineration technologies currently in use across Vietnam. Additionally, research should focus on the utilization of bottom ash after MSW incineration in combination with common local materials, such as soil, sand, and stone. Exploring the reinforcement of these mixtures with varying cement contents for use as construction materials, particularly in road construction, is highly encouraged.

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### Conflicts of Interest

The authors declare no conflict of interest.

### Literatura - References

1. Arm, M. (2000). "Variation in mechanical properties of MSW incinerator bottom ash: Results from triaxial tests". Waste Management Series Vol.1: 567-578.
2. AASHTO Designation (2004). AASHTO M145-91 (2004) "Classification of soils and soil-aggregate mixtures for highway construction purposes".
3. Anh, B. T. (2016). "Research on rational use of waste ash from coal-fired thermal power plants in road construction". PhD. thesis, University of Transport and Communications, Hanoi. (In Vietnamese).
4. ASTM International (2017). ASTM D6913/D6913M-17 "Standard test methods for particle-size distribution (gradation) of soils using sieve analysis".
5. ASTM International (2017). ASTM D1633-17 "Standard test methods for compressive strength of molded soil-cement cylinders".
6. ASTM International (2019). ASTM D2216-19 "Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass".
7. ASTM International (2023). ASTM D854-23 "Standard test methods for specific gravity of soil solids by the water displacement method".
8. Chimenos, J. M., Fernández, A. I., Miralles, L., Rosell, J. R., Ezquerro, A. N. (2005). "Change of mechanical properties during short-term natural weathering of MSWI bottom ash". Environmental Science & Technology Vol.39(19): 7725-7730.
9. Environmental Industry Magazine (09/03/2020). <https://congnghepmoitruong.vn/hop-tac-xa-thanh-cong-tien-phong-trong-linh-vuc-xu-ly-rac-thai-1587.html>. (In Vietnamese).
10. Environmental Management Newspaper (14/01/2024). <https://quanly.moitruongvadothi.vn/15/27092/Viet-Nam-hien-co-bao-nhieunha-may-dot-rac-phat-dien.aspx>. (In Vietnamese).
11. Hjelmar, O., Holm, J., Crillesen, K. (2007). "Utilisation of MSWI bottom ash as sub-base in road construction: first results from a large-scale test site". Journal of Hazardous Materials Vol.139(3): 471-480.
12. Jurgita, M., Edmundas, S., Rimvydas, S. (2023). "The effect of milled municipal solid waste incineration bottom ash on cement hydration and mortar properties". Materials 2023 Vol.16(6) 2528, 14 pages.
13. Lentz, D., Dermars, K. R, Long, R. P., Garrick, N. W. (1994). "Performance and analysis of incinerator bottom ash as structural fill". Final report of the Project 62-6 JHR 94-232. University of Connecticut, Hartford.
14. Muhunthan, B., Taha, R., Said, J. (2004). "Geotechnical engineering properties of incinerator ash mixes". Journal of the Air and Waste Management Association Vol.54(8): 985-991.
15. Ministry of Science and Technology (2005). TCVN 4054:2005 "Highway - Specifications for design". (In Vietnamese).
16. Ministry of Natural Resources and Environment (2009). QCVN 07:2009/BTNMT "National technical regulation on hazardous waste thresholds". (In Vietnamese).
17. Ministry of Science and Technology (2011). TCVN8862:2011 "Standard test method for splitting

- tensile strength of aggregate material bonded by adhesive binders”. (In Vietnamese).
18. Ministry of Science and Technology (2012). TCVN 9436:2012 “Highway embankments and cuttings - Construction and quality control”. (In Vietnamese).
  19. Ministry of Science and Technology (2014). TCVN 10379:2014 “Soils stabilized with inorganic adhesive substances, chemical agent or reinforced composite for road construction - Construction and quality control”. (In Vietnamese).
  20. Ministry of Science and Technology (2020). TCVN 12790:2020 “Soil, aggregates for transport infrastructure - Proctor compaction test”. (In Vietnamese).
  21. Ministry of Science and Technology (2020). TCVN 12792:2020 “Road and foundation materials - Standard test method for California bearing ratio (CBR) in the laboratory”. (In Vietnamese).
  22. Ministry of Science and Technology (2023). TCVN 8858:2023 “Cement Treated aggregate base for road pavement - Construction and acceptance”. (In Vietnamese).
  23. Nhan, C. T. H., Huy, T. N., Tri, N. H. (2014). “Mixture of crushed stone reinforced with fly ash cement and asphalt mortar for rural roads”. In proceedings of the ITST Annual Science and Technology Conference. ITST, Hanoi. (In Vietnamese).
  24. Nu, N. T., Thinh, P. H., Son, B. T. (2019). “Utilizing coal bottom ash from thermal power plants in Vietnam as partial replacement of aggregates in concrete pavement”. *Journal of Engineering V.2019*, Article ID 3903097, 11 pages.
  25. National Assembly of the Socialist Republic of Vietnam (06/12/2023). <https://quochoi.vn/tintuc/Pages/tin-hoat-dong-cua-quoc-hoi.aspx?ItemID=82916#:~:text=Hi%E1%BB%87n%20nay%2C%20Vi%E1%BB%87t%20Nam%20%C4%91ang,ch%C3%B4n%20%E1%BA%A5p%20h%E1%BB%A3p%20v%E1%BB%87%20sinh>. (In Vietnamese).
  26. Ruifeng, X., Youngfu, X., Ming, H., Honggao, Z., Feifei, C. (2016). “Assessment of municipal solid waste incineration bottom ash as a potential road material”. *Road Materials and Pavement Design Vol.18(4)*: 992-998.
  27. Singh, D. and Kumar, A. “Factors affecting properties of MSWI bottom ash employing cement and fiber for geotechnical applications”. *Environment Development Sustainability Vol.22(7)*: 6891-6905.
  28. Tien Phong Newspaper (27/06/2022). <https://tienphong.vn/toan-can-hai-rac-xuan-son-dang-duoc-can-hao-qua-tai-post1449080.tpo>. (In Vietnamese).
  29. Yongfu, X. (2019). “Unconfined compressive strength of municipal solid waste incineration bottom ashes”. *Geotech Geol Eng Vol.37*: 1373-1382.