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Effect of weather aging on volume expansion properties of steel slag

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Abstract: Steel slag, one of the huge industrial waste sources, which has many outstanding advantages (hardness, roughness, angularity, and abrasion resistance) has been used as an aggregate in asphalt concrete to bring many benefits. However, steel slag is rarely used in Portland cement concrete because of concerns that it may give rise to volume expansion. One of the main causes of this problem is that the steel slag contains a considerable amount of free lime. This free lime content can be reduced if it is hydrated or the steel slag is aged by water. Therefore, in this study, the effects of weather aging on volume expansion properties of steel slag will be considered. The pH, free lime and volume expansion tests were carried out on weather-aged steel slag samples (after aged by 1 month, 6 months, 12 months and 30 months) and compared with non-aged one. The results showed that the 6 month-aged, 12 month-aged, and 30 month-aged steel slag samples had low free content, low pH and volume expansion. Additionally, the steel slag is stockpiled for more than 6 months has relatively little volume expansion, meeting requirement of ASTM D492 specifications for aggregate in concrete.

Keywords: Steel slag, volume expansion, pH, free lime, aging.

1. Introduction

Steel slag is a by-product of the steelmaking process. The amount of released slag accounts for about 15% of the volume of steel products [1]. In Vietnam, it is estimated that about 1-1.5 million tons of steel slag are discharged each year [2]. Different types of steel slag are formed that depend on the ingredient and the furnace technology used. Currently, in the world, steel is produced by two main technologies: Basic Oxygen Furnace (BOF); Electric Arc Furnace (EAF) [3]. Steel slag has a darker gray color and higher unit weight than that of natural crushed stone. Steel slag is usually ground and sieved to a certain particle size. Currently, steel slag is used as a granular material for backfill, foundation, subgrade and aggregate for concrete [4]. Due to its high strength, abrasion resistance, stability and bonding, steel slag is often used as aggregate of asphalt concrete for high-grade pavements subjected high traffic volume [2, 5, 6]. Steel slag can be used as coarse and fine aggregate for asphalt concrete. However, it is not recommended to use 100% of both steel slag aggregates because it often creates high porosity, increases the bitumen content and reduces the rutting resistance [7].

Although steel slag aggregate is commonly applicated in asphalt concrete, it is rarely used in cement concrete [1]. Several authors have carried out some studies on the strength and durability of Portland cement concrete using steel slag aggregate [8–11]. The results have shown their outstanding advantages in terms of compressive strength, shrinkage when compared with Portland cement concrete using conventional aggregates. However, the volume expansion of steel slag that easily occurs when free lime (CaO) and periclase (MgO) in steel slag participate in hydration reactions can reduce the strength of concrete [7, 12–15]. The volume expansion mechanism of free MgO can be explained similarly to that of free CaO. However, steel slag generated from modern steelmaking technologies has a very low MgO content. In the chemical hydration mechanism of CaO, a large stress is generated in the concrete [16]. This stress can exceed 30000 Psi (200 MPa). CaO can hydrate almost completely in a relatively short period of time by following equation [17]:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

Free lime (CaO) will react with water to produce $Ca(OH)_2$ resulting in an increase in the volume of the product [18]. This is considered to be the main cause of volume expansion in steel slag [15, 19, 20]. However, some research suggested that steel slag stored at stockpile under weather aging after a period of 3-12 months has much lesser volume expansion because most of the free lime participates in the hydrate reaction [15, 21–23]. In Vietnam today, there have been some studies on the application of steel slag as an aggregate in asphalt concrete and geopolymer concrete, but all use aged steel slag (taken at an outdoor stockpile) [2, 4, 24]. The detail effect of weather aging time on the volume expansion properties of steel slag has never been considered. Therefore, in this study, studies on volume expansion, free lime content, PH, density of Thainguyen steel slag at different aging time will be carried out in this study.

2. Experimental study to evaluate the effect of aging on volume expansion of steel slag

2.1. Material

Steel slag used in the study was taken from Thainguyen iron and steel industry. It is classified to EAF slag. Steel slag was crushed into different particle sizes and recovered the excess metal remaining (metal shavings) by a magnetic furnace device. Steel slag was collected from the factory and brought to the yard (uncovered) for weather aging. Samples were tested at different ages. The photo of the steel slag sample is shown in Fig 1.

Fig 1. Thainguyen Steel Slag

Table 1 shows some mechanical properties of the studied steel slag and Table 2 shows some main oxide components of the studied steel slag. Note that the total CaO content is shown in table 2 is inclusive of both crystalline form silicate calcium and free lime. Normally, free lime that is hydrated and converted to portlandite and causes physical instability volume of slag aggregates.

Table 1. Some mechanical properties of steel slag

No	Targets	Value
1	Density (g/cm^3)	3.74
2	Unit weight (g/cm^3)	3.47
3	Volumetric mass (g/cm^3)	1.89
4	Water absorption (%)	2.21
5	Content of dust, mud, clay (%)	0.31
6	Concentration of flattened lozenges (%)	3.10
7	Loss of LA (%)	13.18
8	Dry compression (%)	8.99
9	Saturation Compression (%)	9.80

Table 2. Some chemical components (main oxides) in the steel slag

CaO	SiO_2	Al_2O_3	MgO	FeO	Fe_2O_3	SO_3(S)
25.26	19.94	6.13	5.89	-	33.22	6.21

MnO	TiO_2	P_2O_5	Cr_2O_3	K_2O	Na_2O
3.29	0.68	0.32	1.06	0.015	-

2.2. Experiment

2.2.1. Volumetric expansion of steel slag

Volume expansion test of steel slag was

conducted according to Standard ASTM D4792 [25]. The molds have dimensions of 15.24x17.7 cm, and the height of the material container is 11.64 cm. The samples were carried out with nominal particle size (D_{max}) of 19 mm. The molds containing samples were put into the water tank (the water level in the tank always maintains 25 mm above the sample surface). The tank should be covered to prevent water evaporation. The slag samples were immersed in a water bath at 74 ± 3°C for the duration of the experiment (7 days) (Fig 2). The strain gauge readings were recorded daily and denoted by last reading. The value of sample height change after immersion was determined on the basis of the end readings and initial readings on the expansion meter. The volume expansion (H_{tn}) is calculated as follows:

$$H_{tn} = \frac{S_c - S_d}{H_0} 100 \quad (2)$$

In there:

S_c: Last reading on strain gauge (mm)

S_d: First reading on strain gauge (mm)

H_o: Initial height of the sample (mm)

Fig 2. Test to determine the volume expansion of steel slag aggregates

2.2.2. Determination of pH

The pH of the steel slag was determined by measuring the potential difference of the electrode as immersed it in the sample extracted solution with a pH meter (according to ASTM D 1293 [26]). The steel slag was crushed into powder that passes through a sieve with a sieve size of 0.14 mm to conduct pH test. Then, taking the 5g powder sample into a 50 ml pure water. The sample container was stirred gently for 5 min to disperse the steel slag powder in the water. The lid was closed to prevent the extract solution contact with air. After 30 min, shake the sample solution again. The sample extract solution was kept to stable for 24h then was tested by pH determination meter.

2.2.3. Determine the content of free lime

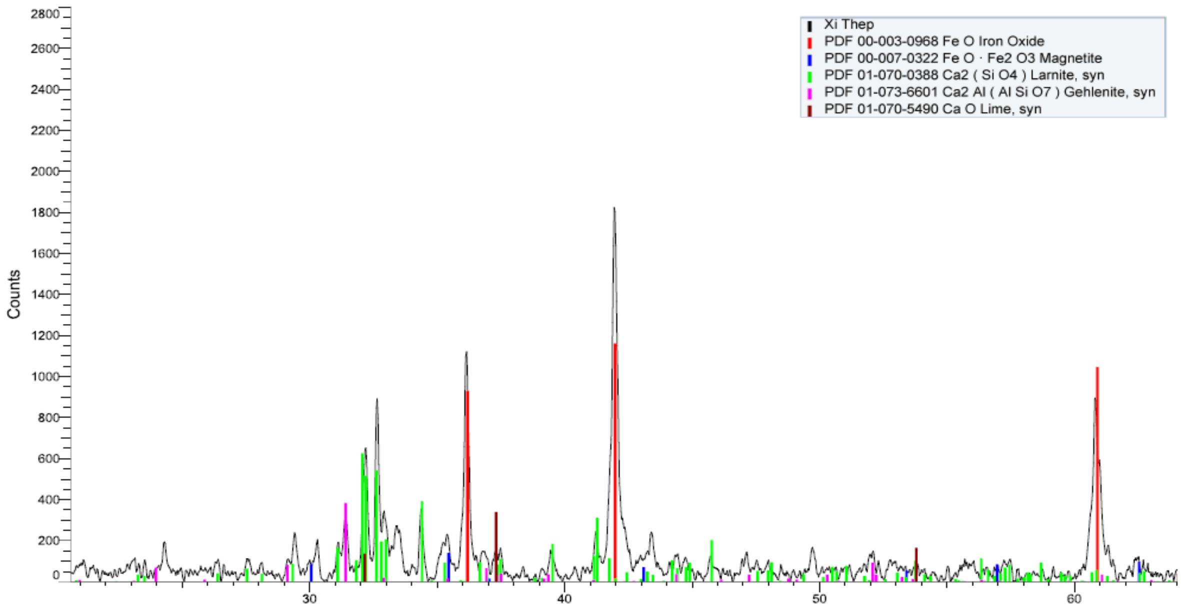
XRD (X-Ray Diffraction) can be used to identify the mineral compound, single crystals and reveal their structure. XRD is particularly useful in geology and material research. For minerals with variable formula and structure, such as clay, XRD is the best method to identify and determine their proportions in a sample. In this study, the test was conducted at the Institute of Chemistry - Vietnam Academy of Science and Technology. Thereby, the free lime content (if any) will be determined. Fig 3 describes the XRD device.

Fig 3. XRD device

3. Results and Discussion

3.1. Free lime content

XRD test is performed for all types of steel slag. The typical XRD image results of non-aged steel slag are shown in Fig 4. The results showed that the main minerals in non-aged steel slag include iron oxide (FeO), Magnetite ($FeO.Fe_2O_3$), Lamite (Ca_2SiO_4), Gehienite ($Ca_2Al(AlSiO_7)$) and free lime (CaO).



Index	Color	Scan	Compound Name	Formula	System	I/Ic DB	S-Q
1		xi thep.brml #1	Iron Oxide	Fe O	Cubic	(1)	49.2 %
2		xi thep.brml #1	Magnetite	Fe O · Fe2 O3	Cubic	(1)	5.9 %
3		xi thep.brml #1	Larnite, syn	Ca2 (Si O4)	Monoclinic	0.760	33.9 %
4		xi thep.brml #1	Gehlenite, syn	Ca2 Al (Al Si O7)	Tetragonal	2.420	6.7 %
5		xi thep.brml #1	Lime, syn	Ca O	Cubic	4.360	4.3 %

Fig 4. XRD image results of non-aged steel slag

The results of free lime content of steel slags are gathered in Fig 5. The results showed that the free lime content was the highest in non-aged steel slag (4.3%). The content of free lime gradually decreases with aging time. At 30 months, free lime was not found in the steel slag sample. Moreover, from the chart, it can be seen that the free lime content in steel slag decreased very quickly in the 6 months. In the first month-aging, the free lime content decreased by almost half compared to that of the original. After 6 month-aging, the free lime content of steel slag is reduced by approximately 80% compared to that of non-aged steel slag.

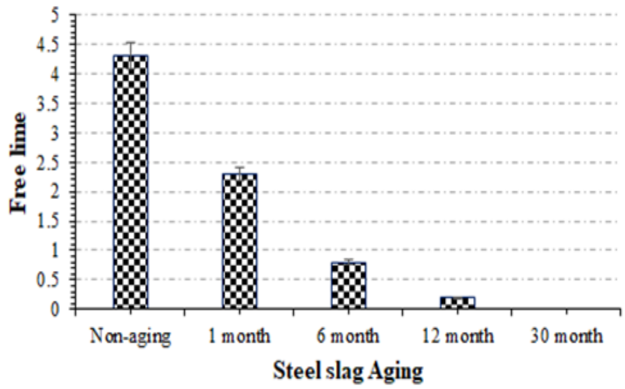


Fig 5. Free lime content of steel slags

3.2. pH value

The pH results of the solution extracted from steel slag at 21 days are shown in Fig 6. The results showed that the pH in the extraction from non-aged steel slag was the highest (9.6), and the solution extracted from the 30 moth-aged steel slag had the lowest pH (8.27). The 1 moth-aged steel slag has a very high pH in solution (9.5), almost similar to that of non-aged steel slag. However, after that, the pH gradually decreased over time. At 6 month-aging, the pH in the solution was significantly reduced by 8.33% compared to that of non-aged slag. At 12 month-aging and 30 month-aging, the pH decreased by 11.45% and by 13.85%, respectively. This is also consistent with the free lime content results above. Non-aged and 1 month-aged steel slag contains a larger amount of free lime than long-term aging steel slag, so the solution extracted from non-aged and 1 month-aged steel slag also show higher pH.

Fig 7 shows the test results of pH value over testing time. The results show that the pH value of different steel slag changed over time with different trend. For non-aged steel slag, there was an increase in pH value and reached the highest value immediately after 1 day of soaking, but decreased gradually. Meanwhile, the aged steel slags seemed to have a gradual increase in pH value and hit the peak after 2 days (for 1 month-aged slag), 3 days (for 6 moth-aged slag) and 5 days (for 12 month-aged and 30 moth-aged slag). However, after 14 days, the pH of the all slag samples remained a relatively stable value.

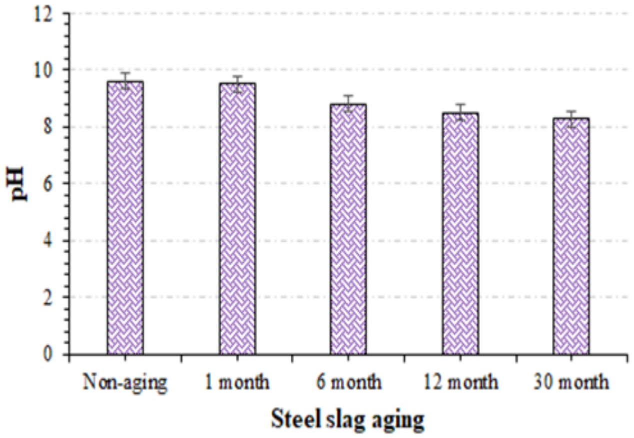


Fig 6. pH results of the solution extracted from steel slag at 21 testing days

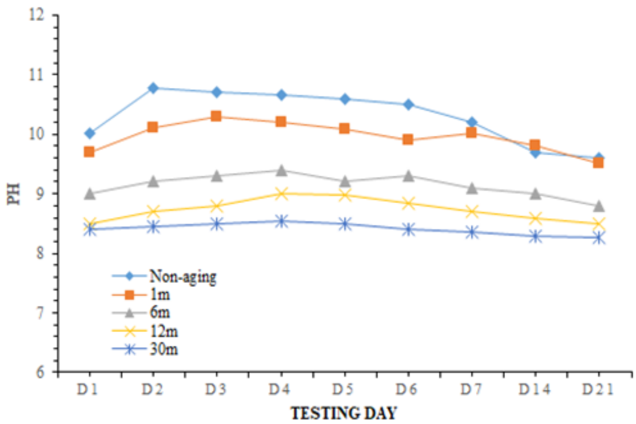


Fig 7. pH value of steel slags over testing time

3.3. Volume expansion degree

The experimental result of steel slag's volume expansion at 7 day-testing are shown in Fig.8. The results show that the volume expansion of non-aged steel slag is the highest (1.72), and the volume expansion of30 month-aged steel slag is the lowest (0.14). It can be seen that the volume expansion of the slag samples decreases with aging time. Steel slag aged by 1 month has reduced volume expansion by 56.9% but still at a very high level (0.74). After 6 months aging, volume expansion was significantly reduced by 77.32% compared with that of non-aged slag. At 12 months aging, volume expansion decreased by 87.2% and decreased by 90.1% at 30 months aging. This is also explained appropriately because for non-aged and 1 month-aged steel slag, the free lime content is still high and strongly participates in the hydration process, creating a large change in volume. That leads to higher volume expansion. It is noticed that free lime was not found in the 30-aged slag, but a very small volume expansion was recorded. Because the volume expansion of steel slag aggregates can be caused by other minerals that hydrolyze with water. However, volume expansion is very small, can be negligible.

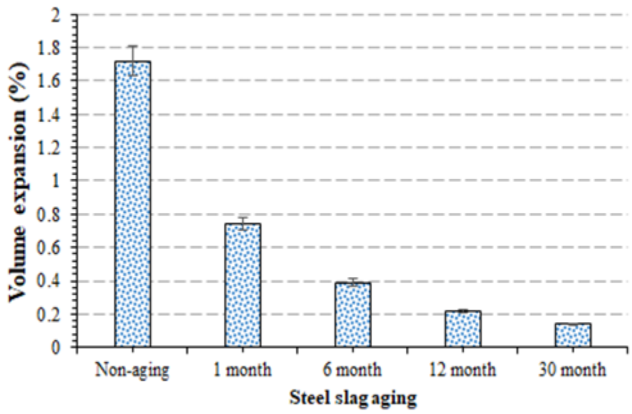


Fig 8. Volume expansion of steel slag at 7 day-testing

Fig 9 shows the experimental results of volume expansion measurement due to the testing time. The results show that the volume expansion of different steel slags changes over time with different trends. For non-aged and 1-month-aged steel slag, volume expansion increases gradually over time from 1st-5th days, but tends to increase slowly from 5th-7th days. Furthermore, non-aged steel slag shows very strong volume expansion as indicated by the stiff slope of the blue line. Meanwhile, 6 moth-aged, 12 month-aged and 30 month-aged steel slag show a slower volume expansion rate, and the increase was also steady and much smaller as indicated by the straight line with very small slope, almost horizontal. Moreover, these steel slags tended to less reduce volume expansion at the 7th testing day.

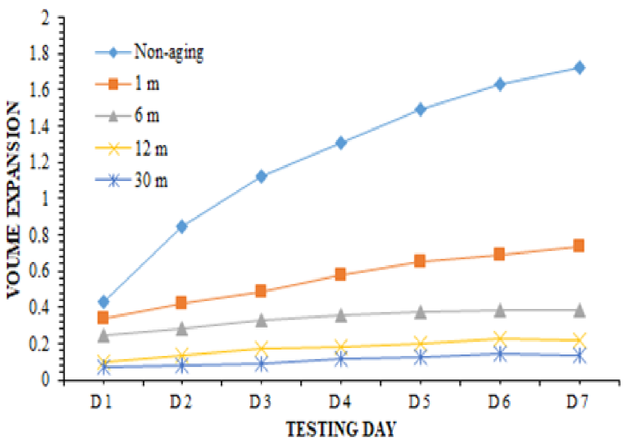


Fig 9. Volume expansion of steel slag over time

The volume expansion values (after 7 testing-day) of 6 month-aged, 12 month-aged and 30 month-aged steel slag are all less than the volume expansion requirement for natural aggregates according to ASTMD4792 (0.5%) [25]. The results of this study are similar to the study of Manso et al. whose test was also performed by ASTM D4792 [11]. The Manso's results show that non-aged steel slag has volume expansion from 0.5% to 2.5%. Steel slag after undergoing outdoor weathering, the volume expansion can be reduced to 0.15% to 0.40% [11]. On the other hand, through the study of mineral composition in Thainguyen steel slag samples, it has been proved that steel slag does not contain free lime after 30 month-aging. Moreover, the steel slags aged more than 6 months have volume expansion less than 0.5% after 7 day-testing, meeting the requirements of ASTMD4792 for natural aggregates. Thus, it can be seen that Thainguyen steel slag, if it undergoes through the outdoor weathering process for a long time (about 6 months), can ensure enough expansion requirements and can be used as a substitute for natural aggregates in concrete. However, it should also be noted that steel slags from different factories, or different production batches can produce different types of steel slag in terms of mineralization properties as well as free lime. Therefore, it is recommended that before using steel slag as aggregate in concrete, steel slag has been sufficiently weathered for a long time and to conduct volume expansion tests.

4. Conclusion

Through experimental studies, weather aging has a very significant influence on the volume expansion properties of EAF steel slag from Thainguyen Iron factory. With non-aged or, 1 month-aged steel slag, the free lime content in the sample is very high, resulting in a high pH value of the extraction solution and volume expansion. However, with weather aging by 6 months, 12 months, and 30 months, the free content of steel slag was much lower, because it was involved in the hydration reactions during the long aging time. Thus, this leads to the lower pH value and volume expansion. In addition, steel slag aged by more than 6 months has very low volume expansion (<0.5%), meeting the requirements of ASTM D492 for aggregate in concrete. Therefore, it is recommended to use steel slag that has been weathered for an enough long time and have to conduct volume expansion tests before using it as an aggregate in concrete. In the future, further studies on volume expansion of steel slag by using other aging measures such as steam aging, autoclave aging will be carried out.

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