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Investigation of using steel slag in hot mix asphalt for the surface course of flexible pavements

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Abstract: The rapid development of heavy industry in Vietnam leads to the establishments of steel industry. Steel slag, a by-product of steelwork industry, under Vietnamese’s law, was considered as a deleterious solid waste which needed to be processed and landfilled. However, this has changed recently, and steel slag is now seen as a normal or non-deleterious solid waste, and has been studied for reuse in the construction industry. In this study, steel slag was used, as a replacement for mineral aggregate, in hot mix asphalt. Two hot mix asphalt mixtures with an equivalent nominal aggregate size of 12.5 (C12.5) and 19 mm (C19) were produced using steel slag. In addition, one conventional hot mix asphalt mixture of C19 was produced using mineral aggregate for comparison purpose. Investigation in laboratory condition and trial sections was carried out on Marshall tests, surface roughness, skid resistance, and modulus of the pavement before and after applying a new surface course of hot mix asphalt. The study showed that all steel slag asphalt mixtures passed the Marshall stability and flow test requirements. The skid resistance of steel slag hot mix asphalt mixtures for the surface course satisfied the Vietnamese specification for asphalt. Moreover, the pavement sections with the surface course of steel slag hot mix asphalt showed a considerable higher modulus than that of the conventional one. Only the roughness of the surface course paved with C19 did not pass the requirement of the specification.

1. Introduction
Sustainable development is an vital goal of many countries in the world. Rapid development demands a great need of heavy industries which produce the required material. Vietnam is a developing country with a rapid development of heavy industries. In steel industry, there is a huge demand for steel production for the domestic use. This requirement results in a numerous new steel mills. As a result, more steel slag, a by-product from steel industry, is being produced. In Vietnam, a few years ago, steel slag was considered as a deleterious solid waste which needed to be processed and landfilled. However, nowadays steel slag is seen as a normal, non-deleterious solid waste, and has been studied for reuse in construction industry such as making concrete or brick block. So far, the recycling of steel slag in the road construction in Vietnam is still very limited.

Although steel slag is paid attention for reuse in the construction industry, the recycling of this material in road construction in Vietnam still lags behind compared to other countries. In USA, Japan, German and France, the reuse of steel slag is close to 100% [1]. The reuse of steel slag is highly concentrated to road construction in developed countries, with more than 50% of steel slag is used
directly for road projects [2]. Until now, there are a number of official guidelines in English for the reuse of steel slag, which can be easily found by using online searching tools, such as [3] for using steel slag in roads published by Australian Slag Association, or in report [4] for the use of steel slag in pavements in Washington state, USA. Although there are many countries reusing steel slag as a pavement material, the application of the material in pavement is still a concern for developing countries like Vietnam. The reasons being are the suitability of the material to replace traditional mineral aggregate and especially whether the material is contaminating to the environment. The concern of contamination of the environment is understandable as steel slag, a by-product of steel production, is different based on different technologies applied in the production procedure. In a developing country like Vietnam the technology in steel industry may not be as advanced as in developed countries hence the by-product may contain chemical elements that are deleterious to the environment and human.

Study [5] investigated whether steel slag is suitable for road base shows that steel slag contained high percentage of CaO which is sensitive to water and may change the volume of the material. This study indicated that steel slag may lose stability if water is present due to volume expansion. After that, steel slag was conditioned in moisture for six months and grinded for experiments. At this stage, steel slag showed quite high modulus, even higher than mineral aggregate for road base. The study concluded that steel slag can be used for road after moisture treatment to reduce the volume change possibility before application [5]. Another study [6] also investigated the possibility of using steel slag for road base and it concluded that the road base of 100% steel slag still worked well after a number of floods due to poor drainage system. The mentioned studies show that steel slag can be used for road base. However, in the manual on the use of steel slag in the United States, the alkalinity leach from steel slag is warn may exceeds 11 pH. Excessive pH levels of leachate can corrode sewers and affect aquatic ecological environment surrounding the road construction site [4]. Therefore, it is very important and necessary to determine the pH of steel slag prior to use for the road base.

Steel slag was also studied for use in asphalt concrete. Since the 1990s, steel slag has been used for asphalt concrete in Australia, USA [3] [4]. The advantages of steel slag compared to natural stone materials are the high roughness, high porosity and good strength. In 1991, Ali and his colleagues conducted a study on the stability of asphalt concrete in Canada using steel slag [7]. The research showed that higher steel lag content in asphalt concrete increased its elastic modulus, decreased deformation, increased compressive strength, and less susceptible to water [7]. However, using 100% steel slag would require a higher bitumen content of 25% than the mineral aggregate [7]. The research [7] did not mention the possibility of expanding the volume of steel slag affecting the actual work of asphalt concrete in fields. Therefore, a number of studies have been conducted to evaluate the effects of the volume expansion of steel lag on the performance of asphalt concrete [8] [9]. The results showed that high steel slag content in asphalt concrete caused cracking of asphalt concrete due to the effect of water [8] that causes expansion of steel slag [9]. The study [8] also recommended that a suitable test to check the expansion of the slag before use is needed.

2. Research aim and scope
This research aims to study the ability of recycling steel slag in hot mix asphalt for the surface course of road pavement in Vietnam. Firstly, the chemical and physical properties of steel slag were studied to evaluate the applicability of the material for production of hot mix asphalt. Asphalt mixtures were later prepared with steel slag and mineral aggregate. Two hot mix asphalt mixtures with nominal aggregate sizes of 12.5 and 19 mm were produced using steel slag, and one hot mix asphalt mixture with the nominal aggregate size of 12.5 mm was produced using mineral aggregate for comparison purpose. Investigation in laboratory condition and trial sections was carried out on Marshall tests, surface roughness, skid resistance, and modulus of the pavement, before and after applying a new surface course of hot mix asphalt.

3. Material and mixture preparation
3.1 Material

In the beginning of the project, samples of steel slag were collected and evaluated on basic physical and chemical properties to check the applicability of using steel slag as a replacement material for mineral aggregate in production of hot mix asphalt. It should be noticed that the properties of steel slag presented here are for raw material which had not yet grinded and classified for gradation. The properties of steel slag were determined in accordance to Vietnamese standards as shown in Table 1.

Table 1: Physical and chemical properties of steel slag.

| Order | Physical property                                      | Standard          | Result | Unit  |
|-------|-------------------------------------------------------|-------------------|--------|-------|
| 1     | Apparent Specific Gravity                            | TCVN 7572-4:2006  | 3.5    | g/cm³ |
| 2     | Bulk Specific Gravity                                | TCVN 7572-4:2006  | 3.24   | g/cm³ |
| 3     | Bulk Saturated Surface Dry (SSD) Specific Gravity    | TCVN 7572-4:2006  | 3.32   | g/cm³ |
| 4     | Water absorption                                     | TCVN 7572-4:2006  | 2.07   | %     |
| 5     | Bulk density                                         | TCVN 7572-6:2006  | 1826   | Kg/m³ |
| 6     | Voids between aggregate particles                    | TCVN 7572-6:2006  | 46.86  | %     |
| 7     | Content of dust, mud and clay in aggregates          | TCVN 7572-8:2006  | 0.95   | %     |
| 8     | Los Angeles abrasion                                  | TCVN 7572-12:2006 | 20.8   | %     |
| 9     | Elongated particles                                  | TCVN 7572-13:2006 | 0.74   | %     |
| 10    | Volume change due to water                           | 22TCVN 333:06     | 0      | %     |
| 11    | CBR                                                   | 22TCVN 333:06     | 90.68  | %     |
| 12    | Modulus of aggregate                                 | 22TCVN 211:06     | 230.7  | MPa   |

| Order | Chemical property (by weight of sample)              | Standard          | Result  | %     |
|-------|------------------------------------------------------|-------------------|---------|-------|
| 1     | SiO₂                                                 | TCVN 7131-2002    | 15.358  |       |
| 2     | Al₂O₃                                                | TCVN 7131-2002    | 7.1     |       |
| 3     | Fe₂O₃                                                | TCVN 7131-2002    | 34.7    |       |
| 4     | CaO                                                  | TCVN 7131-2002    | 24      |       |
| 5     | MgO                                                  | TCVN 7131-2002    | 5.09    |       |
| 6     | Sunphat, sunphit                                     | TCVN 7131-2002    | 0.088   |       |

Based on the results from Table 1, it can be seen that the specific gravity of steel slag (3.5 g/cm³) is larger than typical mineral aggregates which are normally around 2.7 g/cm³. Steel slag has higher water absorption but very stable with water as the volume change due to water is zero. The content of dust, mud and clay in steel slag is rather low, 0.95%. This may reduce the binder adhesion. However, as the test was carried out on the material before grinding, the amount of dust, must and clay can be adjusted depending on the purpose of the mix design. There is also an interesting notice that the voids in steel slag is high, and the surface of steel slag is rough which would increase the binder adhesion. Steel slag has a very small amount of elongated particles, 0.74%, meaning that the material satisfying the requirement of flat and elongate particles of aggregate for asphalt mixtures. Los Angeles abrasion resulted in 20.8% of aggregate mass abraded. The value satisfies the toughness requirement of aggregate for Hot Mix Asphalt (HMA). Basically the results shown here for physical properties of steel slag satisfied the requirement for aggregate for production of HMA. In terms of chemical properties, Fe₂O₃, SiO₂ and CaO dominate the mass of the material, accounting for roughly 74% of steel slag mass. Al₂O₃ and MgO account for around 12.2% of the material mass. The component contents should be different for different technologies and source of mine.

3.2 Mixture design
Two hot mix asphalt mixtures with steel slag were designed then produced at an asphalt plant for placement and compaction at a trial section. The maximum nominal aggregate sizes of the two mixtures are 12.5 and 19 mm, abbreviated as C12.5 and C19 respectively. There was a control HMA mixture produced with mineral aggregate with the maximum nominal aggregate size of 12.5 mm. The gradations of the two asphalt mixtures aggregate are shown in Figure 1 and Figure 2.

![Figure 1: Aggregate gradation of HMA steel slag with nominal aggregate size of 12.5 mm](image1)

![Figure 2: Aggregate gradation of HMA steel slag with nominal aggregate size of 19 mm](image2)

The optimum binder contents were designed according to Vietnamese specification. To determine the optimum binder content, five different binder contents were chosen to produce samples, and three replicas were prepared at each binder content. It should be noticed that the apparatus in this study followed Marshall mix design procedure, and samples with the diameter of 100 mm and height of 57 mm were prepared. The optimum binder contents for HMA using steel slag were 5.13 % and 4.92 % of the mixture weight for C12.5 and C19 respectively.

3.3 Mixture production

After designing the mixtures at laboratory condition, HMA mixtures with steel slag were produced at a local asphalt plant in Vung Tau, Vietnam. The mixing plant has an automatic batched mixing mechanism, originally from South Korea with the capacity of producing up to of 80 tons per hour. The mixing procedure of HMA using steel slag is similar to the mixing procedure of HMA using mineral aggregate. The heating temperature of steel slag was 170°C and bitumen was heated to 140°C for mixing. The mixing time was 40 seconds. After mixing, HMA steel slag was loaded on a specialised truck and transported to the trial section site for placement and compaction. Figure 3 illustrates main works at the mixing plant.
Figure 3: Main works of production of steel slag HMA at the asphalt plant

4. Trial section preparation and testing

4.1 Trial section preparation
The trial section road is the end section of a road in Quang Phu – Phuoc An, Chau Duc district, Ba Ria-Vung tau province, Vietnam. This road section had two lanes, and each lane is 3.5 m wide. The existing pavement was chip seal one which was planned to be upgraded to HMA surface course. The C12.5 steel slag HMA mixture was paved roughly 20 m long and C19 steel slag HMA mixture was paved approximately 15 m long (Figure 4). Before the construction, the modulus at 15 different positions in five cross section of the existing pavement were checked (Figure 4). The purpose of this is to have a comparison with the modulus of the pavement after surfacing which will be discussed in Section.

Figure 4: Trial section paving scheme and modulus checking positions

4.2 Testing

4.2.1 Surface roughness test.
The surface roughness test was carried out in this study by using a 3.0 m straight edge. The procedure was followed as described in Vietnamese specification TCVN 8864:2011. The straight edge was placed at three different positions at a chosen cross section as illustrated in Figure 5. The heights of the gaps between the straight edge and the road surface were determined by using a wedge designed as a ruler.
The gap heights are presented in Tables 2 and 3. According to Vietnamese specification, there are three levels of surface roughness: very good, good, and medium. For surface course of hot mix asphalt, the level “very good” requires 70% of gap heights are not greater than 3 mm, and the rest 30% gap heights are not greater than 5 mm. For the level “good”, 50% of gap heights should not be larger than 3 mm, and the rest 50% should not be larger than 5 mm. For the level “medium”, 100% gap heights should not exceed 5 mm.

![Figure 5: Surface roughness checking scheme](image)

**Table 2**: Surface roughness test results of steel slag hot mix asphalt C12.5 surface course

| Cross section | Checked Position | Number of gaps between the 3 m straight edge and road surface , x (mm) |
|---------------|------------------|---------------------------------------------------------------------|
|               |                 | x<3   3<x≤5 5<x≤7 7<x≤10 10<x≤15 15<x≤20 x>20 |
| 1             | P1               | 6      1       0       0       0       0       0       |
|               | P2               | 4      3       0       0       0       0       0       |
|               | P3               | 5      2       0       0       0       0       0       |
| 2             | P4               | 6      1       0       0       0       0       0       |
|               | P5               | 6      1       0       0       0       0       0       |
|               | P6               | 7      0       0       0       0       0       0       |
| 3             | P7               | 3      4       0       0       0       0       0       |
|               | P8               | 6      1       0       0       0       0       0       |
|               | P9               | 6      1       0       0       0       0       0       |
| Sum of checked position | 63 | 49 | 14 | 0 | 0 | 0 | 0 | 0 |
| % of total position | 78% | 22% | 0% |
Table 3: Surface roughness test results of steel slag hot mix asphalt C19 surface course

| Cross section | Checked Position | Number of gaps between the 3 m straight edge and road surface, x (mm) |
|---------------|-----------------|---------------------------------------------------------------|
|               |                 | $x<3$  $3<x \leq 5$  $5<x \leq 7$  $7<x \leq 10$  $10<x \leq 15$  $15<x \leq 20$  $x>20$ |
| 1             | P1              | 6     1     0     0     0     0     0                      |
|               | P2              | 6     1     1     0     0     0     0                      |
|               | P3              | 5     2     0     0     0     0     0                      |
| 2             | P4              | 4     3     0     0     0     0     0                      |
|               | P5              | 5     2     0     0     0     0     0                      |
|               | P6              | 7     0     0     0     0     0     0                      |
| 3             | P7              | 3     4     0     0     0     0     0                      |
|               | P8              | 6     0     1     0     0     0     0                      |
|               | P9              | 5     2     0     0     0     0     0                      |
| Sum of checked position |       | 64    47    15    2     0     0     0                      |
| % of total position   |       | 73%   23%   3%                                  |

4.2.2 Skid resistance test.
The skid resistance tests of the road surface used in this study was sand patch test method. The procedure was described in Vietnamese specification TCVN 8866:2011. This procedure in Vietnamese specification is similar to that in ASTM E 965. To carry out the test, dry road surface must be prepared. A known quantity of sand was poured onto the surface and spread in a circle. When the sand cannot be spread any more, the sand circle was measured and recorded in mm. As the sand quantity is known, the average texture depth is known by utilizing the measured diameter. Similar to the surface roughness test, three cross sections were chosen to test for each mixture. However, there were two positions checked per cross section rather than three as in the surface roughness test. According to the requirement of Vietnamese standard for skid resistance, the texture depth value of a newly built surface course constructed by hot mix asphalt should be equal to or greater than 0.45 mm. As can be seen in Table 4, the average values of texture depth are equally 0.47 for both C12.5 and C19, meaning that the skid resistance of the surface courses constructed by steel slag hot mix asphalt satisfied the requirement of skid resistance for hot mix asphalt.

Table 4: Sand patch test results for steel slag hot mix asphalt surface courses for C12.5 and C19

| Mixture | Value determined in mm | Cross section 1 | Cross section 2 | Cross section 3 | Average | CoV (%) |
|---------|------------------------|----------------|----------------|----------------|---------|---------|
|         | Diameter of sand circle| P1  P2  P1  P2  P1  P2 | 262.8  259.5  260.9  258.6  262.1  261.3 |
| C12.5   | Texture depth          | 0.46  0.47  0.47  0.48  0.46  0.47  0.47  0.47  0.47  0.47  1.61 |
| C19     | Diameter of sand circle| 257.9  260.7  260.3  259.3  260.1  260.9 |
|         | Texture depth          | 0.48  0.47  0.47  0.47  0.47  0.47  0.47  0.47  0.47  0.87 |

4.2.3 Marshall stability and flow test.
Cores from paved surface course of steel slag HMA mixtures were subjected to Marshall stability and flow test to check the compliance of the mixtures to the requirement of Vietnamese specification. Three samples were cored for each test purpose. Totally 6 samples were cored and tested and their locations...
are shown in Figure 6. The results of tests are shown in Table 5. The Marshall stability requirement is addressed in TCVN 8819-2011, in which the value should be equal to or greater than 6 kN. It can be seen that the Marshall stability of the two mixtures satisfied the requirement from of the Vietnamese specification. Similar to the Marshall stability, the flow test of the samples from the two mixtures also passed the requirement of Vietnamese specification, TCVN 8819-2011, in which the results all fall into the requirement range of 2 – 4 mm.

**Figure 6:** Coring scheme to prepare samples for Marshall stability and flow test

**Table 5:** Marshall stability and flow test results

| Mixture | Sample | Marshall stability (kN) | Specification's Requirement (kN) | Satisfaction | Flow test (mm) | Specification's Requirement (mm) | Satisfaction |
|---------|--------|-------------------------|---------------------------------|--------------|---------------|---------------------------------|--------------|
| C12.5   | 1      | 11.08                   | ≥ 6.0                           | Yes          | 3.81          | 2 - 4                           | Yes          |
|         | 2      | 11.72                   | ≥ 6.0                           | Yes          | 3.86          | 2 - 4                           | Yes          |
|         | 3      | 11.62                   | ≥ 6.0                           | Yes          | 3.78          | 2 - 4                           | Yes          |
|         | Average| 11.47                   | ≥ 6.0                           | Yes          | 3.82          | 2 - 4                           | Yes          |
| C19     | 1      | 12.44                   | ≥ 6.0                           | Yes          | 3.56          | 2 - 4                           | Yes          |
|         | 2      | 12.36                   | ≥ 6.0                           | Yes          | 3.51          | 2 - 4                           | Yes          |
|         | 3      | 12.49                   | ≥ 6.0                           | Yes          | 3.71          | 2 - 4                           | Yes          |
|         | Average| 12.43                   | ≥ 6.0                           | Yes          | 3.59          | 2 - 4                           | Yes          |

4.2.4 Modulus.

The Modulus of the pavement is used to evaluate the loading resistance capacity. To compare the load bearing capacity of steel slag HMA, the modulus of the pavement after surfacing steel slag was compared with the modulus of the pavement after surfacing the control HMA C12.5. It should be noted that the layer thickness of both steel slag and mineral HMA mixtures were both equaly 7 cm. Before surfacing, the modulus of pavement was checked as mentioned previously in this paper. The checking positions before surfacing can be seen as in Figure 4 and the positions after surfacing can be seen in Figure 7. The modulus of the pavement was checked by using Benkeman beam method following Vietnamese specification TCVN 8867 : 2011. The moduli of pavement before and after surfacing are shown in Table 6. Before surfacing, the average modulus of pavement of the road section with C12.5 surface course with steel slag HMA and mineral HMA are similar, while the average modulus at C19 mixture section is slightly higher than the others. After surfacing, as can be seen from Table 6 that the moduli of the pavement with steel slag HMA mixtures were higher than that of mineral aggregate HMA. It means that the steel slag HMA had higher modulus than that of mineral HMA. This makes steel slag HMA possible to replace for traditional HMA. Although the study did not investigate why the steel slag
HMA performed better than control HMA in terms of modulus, it can be explained that the steel slag has strong resistance to abrasion and the surface texture of steel slag allows better interlocking between particles and adhesion with bitumen. This resulted in higher modulus than that of mineral aggregate HMA mixture. In terms of steel slag HMA mixtures with different nominal sizes, the pavement with larger nominal size showed slightly higher modulus than that of smaller nominal aggregate size. However, as before surfacing, the average modulus of the pavement section with C12.5 was smaller than that with C19. Thus, it is thought that the nominal aggregate size did not significantly differentiate the moduli of C12.5 and C19 mixtures in this study.

![Figure 7: Checking scheme for modulus of pavement](image)

### Table 6. Pavement modulus results of two steel slag HMA and a mineral aggregate HMA

| Mixture               | C12.5 - Steel slag HMA | C19 - Steel slag HMA | C12.5 - Mineral aggregate HMA |
|-----------------------|------------------------|----------------------|--------------------------------|
|                       | Before surfacing       | After surfacing      | Before surfacing | After surfacing | Before surfacing | After surfacing |
| Position              | Modulus (Mpa)          | Position Modulus (Mpa) | Position Modulus (Mpa) | Position Modulus (Mpa) | Position Modulus (Mpa) | Position Modulus (Mpa) |
| P1                    | 141.2                  | P1                    | 209                | P7                   | 151.2                | P6                   | 213.1                | P13                   | 155.2                | P10                   | 191.2                |
| P2                    | 152.5                  | P2                    | 208.4              | P8                   | 173.4                | P7                   | 212.2                | P14                   | 165.3                | P11                   | 190.5                |
| P3                    | 155.2                  | P3                    | 209.6              | P9                   | 168.5                | P8                   | 209                  | P15                   | 163.8                | P12                   | 190.2                |
| P4                    | 173.4                  | P4                    | 207.2              | P10                  | 173.4                | P9                   | 207.2                |                       |                      |                       |                      |
| P5                    | 177.1                  | P5                    | 203.3              | P11                  | 162.1                |                       |                      |                       |                      |                       |                      |
| P6                    | 165.3                  |                       |                    |                      |                      |                       |                      |                       |                      |                       |                      |
| Average               | 160.8                  |                       | 207.5              | 167.7                | 210.4                | 161.4                | 190.6                |                       |                      |                       |                      |
| CoV(%)                | 8.48                   |                       | 1.21               | 5.76                 | 1.31                 | 3.38                 | 0.27                 |                       |                      |                       |                      |

5. Conclusions

This paper presented the application of steel slag for hot mix asphalt to replace mineral aggregate in Vietnam. The results are very promising for future application and this work can be seen as a great effort in recycling waste materials in Vietnam. Some conclusions are drawn below:

- Steel slag has good and comparable physical properties to mineral aggregate to produce hot mix asphalt. Although the steel slag is heavier than general mineral aggregate, it is quite good in terms of water stability
- Steel slag used to be considered as a deleterious waste which needed to be processed and landfilled. However, the results show that the material is not deleterious and can be recycled as a mineral material
- Steel slag HMA mixtures complied with Vietnamese specifications in terms of Marshall Stability and flow test. The two steel slag HMA mixtures can be applied as surface courses in terms of skid resistance as they all passed the tests by using sand patch method
Pavements with steel slag HMA surface course showed higher moduli than that with control mineral aggregate HMA indicating that the two steel slag HMA mixtures had greater moduli than HMA with mineral aggregate.

The C12.5 passed the Surface’s roughness test with level “very good” whereas the C19 failed in accordance to Vietnamese standard. It should be noted that except this test, all the other tests described in this paper passed the specifications’ requirements. Thus, for future application of C19 as a surface course, further surface roughness needs to be checked on trial section before any practical application.

Further research on steel slag is planned to be investigated in Vietnam at a more advanced level covering fatigue and rutting resistance of steel slag HMA mixture. From the preliminary results in this study, it can be concluded that recycling steel slag for hot mix asphalt is applicable and beneficial for sustainable development of Vietnam.

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