A Study on Mixing Proportion of Roller-Compacted Concrete Pavement Made of EAF Slag Aggregate and Fly Ash by Using Taguchi Method

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Abstract. The aim of this study is to investigate the effect of factors in mixing proportion on the dry density of Roller-compacted concrete pavement made of EAF slag aggregate and fly ash by using Taguchi method. In this study, EAF slag with size in range of 4.75 – 19 mm was used as a substitute for natural coarse aggregate with three percentages (i.e. 0%, 50% and 100%). Cement was partially replaced by fly ash at three content levels (i.e. 0%, 20% and 40%). Four factors are considered to study including the percentage of EAF slag aggregate, the percentage of binder (cement + fly ash), the fly ash ratio, and the moisture content. And, three levels of four factors were proposed to study the influence of them on the dry density of RCCP. Thus, nine mixtures conforming the orthogonal array L₉ of Taguchi method were prepared to determine the dry density of RCCP by Proctor test. The results were assessed by the analysis of variance (ANOVA). The results of this research indicated that increasing of the percentage of EAF slag as aggregate replacement led to rise the dry density, whereas increasing of the fly ash ratio as cement substitution resulted in the decrease of dry density. The percentage of binder is range of 10-14% and moisture content in range of 6-8% affected slightly on the dry density. When the moisture content exceeded 8% leading to the reduction of the dry density.

1. Introduction
Electric Arc Furnace (EAF) slag is a by-product of steel production, which is generated during the manufacture of crude steel by the Electric Arc Furnace process. World crude steel production reached 1,621 million tons for the year 2015 leading to the world output of EAF slag was estimated in the range of 170 -250 million tons [1], [2]. The traditional stockpile method of EAF slag has created challenging environmental issues such as a lack of waste storage areas and pollution of soil and underground water. Nowadays, many researches on EAF slag as aggregate replacement in conventional concrete, high-performance concrete, and alkali-activated concrete are found in literature. And, scholars have demonstrated that EAF slag can replace natural aggregates in many kinds of concrete [3]–[8]. For example, the replacement of natural aggregates by EAF slag in conventional concrete led to increase compressive strength and splitting tensile strength [3], [4], [6], [7]. Similarly, the increase of mechanical properties in high-performance concrete made of EAF slag aggregate was also observed [5]. Furthermore, alkali-activated concrete containing steel slag as coarse aggregate attained sufficient strength for structure, whereas the values of durability reduced slightly [8]. But very
few reports conducted on the using of EAF slag as aggregate in Roller-compacted concrete. Roller-compacted concrete is a stiff and no-slump concrete, which is usually used for pavement (called Roller-compacted concrete pavement) due to its fast construction and cost efficiency. Because aggregate in Roller-compacted concrete pavement (RCCP) mixture consists of 75% volume, the substitution aggregate in RCCP by EAF slag is very important to limit the natural aggregates consumption. In addition, fly ash as cement alternative in RCCP has created several benefits in concrete industry [9]–[11]. Mardani-Aghabaglou et al. studied the mechanical and durability properties of RCCP using 20%, 40%, and 60% of fly ash as a partial cement substitution. It is reported that there was a slight decrease in the strength and durability values as fly ash content increased at early ages. However, at later ages, the development of strength and durability attained satisfactory level for pavement application [9]. The similar results are found in Yerramala and Babu research [10]. It was observed that RCCP mixtures with moderate amount of cement ranging from 150 to 190 kg/m³ and fly ash percentage ranging from 60% to 70% performed low values of the permeability, absorption, sorption and chloride diffusivity.

Based on the previous research, the incorporation of EAF slag aggregate and fly ash in Roller-compacted concrete pavement (RCCP) is proposed an effective solution to reduce the environmental impacts and develop a sustainable infrastructure. In this study, EAF slag was used as a substitute for natural coarse aggregate with three percentages (i.e. 0%, 50% and 100%). And, cement was partially replaced by fly ash at three content levels (i.e. 0%, 20% and 40%). RCCP is compacted by vibratory rollers to attain a target density and homogeneous surface pavement [12]. RCCP mixture should be dry enough to maintain the stability of vibratory roller and wet enough to distribute the paste. Hence, RCCP mixing proportion has to be calculated carefully. Soil compaction method is the popular approach to determine the optimum moisture content and maximum dry density of RCCP mixture. Typically, mixtures compacted with maximum dry density would provide the highest performance, especially strength. Therefore, an assessment the influence of materials (i.e. aggregate, binder, and water content) on dry density of mixture is important to enhance strength of RCCP.

Taguchi method developed by Genichi Taguchi is an approach provides an efficient way to optimize designs and keep the experimental cost at the minimum level. A set of orthogonal arrays (OA) to design experiments was designed in Taguchi method [13]. The using of OA provides the optimum working conditions of the affected factors. In addition, Taguchi method allows finding out the effective parameters of target value. Taguchi method is suitable for a wide range of applications. In recent years, Taguchi method has been interested by some scholars in civil engineering. For instance, Joshaghani et al. [14] was used Taguchi method to optimize the performance of density, strength, porosity, and permeability on pervious concrete pavement. Furthermore, Ozbay et al. [15] determined the optimum levels of parameters in mix proportion of high strength self-compacting concrete by Taguchi method. Additionally, Tanyildizi et al. [16] conducted the thirty-two experiments conforming the orthogonal array L₃₂ of Taguchi method to analyze the effects of the polymerization type, the percentage of silica fume, and heating degree on the concrete strengthened with polymer after exposure to high temperature.

The aim of this study is investigation the effect of factors of mixing proportion (i.e. EAF slag aggregate, cement, fly ash, and water content) on dry density of RCCP by Taguchi method.

2. Method

2.1. Materials

Ordinary Portland Cement (OPC) type I conforming to ASTM C150 was used in this study [17]. Class F fly ash conforming to ASTM C618 [18] replaced cement. Table 1 shows the chemical composition and physical characteristics of OPC and fly ash.

Natural aggregates used in this study with gradation as shown in Table 2 is crushed stone. EAF slag aggregate with size in range of 4.75-19 mm (Figure 1) was used to replace natural coarse aggregate in mixture. The properties of natural aggregates and EAF slag aggregate conform to ASTM C33 [19] for concrete making (Table 3).
Table 1. Chemical composition and physical properties of OPC and fly ash

|                             | OPC, Type I | Fly ash, Class F |
|-----------------------------|-------------|------------------|
| **Chemical composition (%)**|             |                  |
| Silica (SiO₂)               | 20.7        | 52.3             |
| Alumina (Al₂O₃)             | 4.5         | 24.9             |
| Ferric oxide (Fe₂O₃)        | 3.3         | 14.1             |
| Calcium oxide (CaO)         | 63.0        | -                |
| Magnesium oxide (MgO)       | 1.8         | -                |
| Sodium oxide (Na₂O)         | 0.10        | 0.67             |
| Potassium oxide (K₂O)       | 0.74        | -                |
| Sulphuric anhydride (SO₃)   | 2.3         | 0.47             |
| Loss on ignition (LOI)      | 2.8         | 0.15             |
| **Physical characteristics**|             |                  |
| Fineness (Blaine) (m²/kg)   | 347         | 289              |
| Specific gravity            | 3.14        | 2.40             |
| Initial setting time (min)  | 110         | -                |
| Final setting time (min)    | 170         | -                |
| Retaining on 45 µm sieve (%)| -           | 7.92             |
| **Compressive strength (N/mm²)**|         |                  |
| 1 day                       | 14.6        | -                |
| 3 days                      | 26.2        | -                |
| 7 days                      | 33.0        | -                |
| 28 days                     | 43.0        | -                |

Table 2. The suggested limits and the designing gradation of RCCP used in this study

| Sieve size | Passing mass (%) |
|------------|------------------|
|            | The lower limit  | The upper limit | The designing gradation |
| 19 mm      | 95               | 100             | 100                      |
| 12.5 mm    | 70               | 95              | 83                       |
| 9.5 mm     | 60               | 85              | 73                       |
| 4.75 mm (No. 4) | 40               | 60              | 54                       |
| 2.36 mm (No. 8) | 30               | 50              | 41                       |
| 1.18 mm (No. 16) | 20               | 40              | 30                       |
| 600 µm (No. 30) | 15               | 30              | 22                       |
| 300 µm (No. 50) | 10               | 25              | 15                       |
| 150 µm (No. 100) | 2                | 16              | 10                       |
| < 75 µm (No. 200) | 0                | 8               | 7                        |

Table 3. Physical properties of the crushed stone and EAF slag aggregate

| Properties                  | Crushed stone | EAF slag |
|-----------------------------|---------------|----------|
|                             | Fine aggregate (4.75 - 0 mm) | Coarse aggregate (19 - 4.75 mm) | Coarse aggregate (19 - 4.75 mm) |
| Apparent specific gravity   | 2.71          | 2.72     | 3.40       |
| Density (OD) (kg/m³)        | 2609          | 2680     | 3085       |
| Density (SSD) (kg/m³)       | 2644          | 2691     | 3176       |
| Bulk density (kg/m³)        | 1493          | 1466     | 1686       |
| Water absorption (%)        | 1.36          | 0.44     | 2.93       |
| Los Angeles abrasion (%)    | NA            | 13.98    | 19.37      |

Note: NA means not available
2.2. Testing Approach

Four factors of mixture affected on dry density of RCCP in this study are considered:

- The percentage of EAF slag aggregate replaced natural coarse aggregate in the mixture.
- The percentage of binder (cement + fly ash) is a ratio of the weight of binder and total the weight of binder plus the weight of aggregates in the mixture.
- The moisture content of mixture is a ratio of the weight of water and total the weight of binder plus the weight of aggregates in the mixture.
- The fly ash ratio replaced cement in the mixture.

Typically, the weight of binder was in range of 10-14% of total weight of binder and oven-dried aggregates in the mixture. And, the moisture content of the mixture was in range of 6-10% [12]. Therefore, three levels of four factors were proposed to investigate the effect of them on mix proportions as shown in Table 4.

| No. | Factors                | ID. | Level 1 | Level 2 | Level 3 |
|-----|------------------------|-----|---------|---------|---------|
| 1   | EAF slag aggregate     | E   | 0%      | 50%     | 100%    |
| 2   | Binder                 | B   | 10%     | 12%     | 14%     |
| 3   | Moisture content       | M   | 6%      | 8%      | 10%     |
| 4   | Fly ash                | F   | 0%      | 20%     | 40%     |

For four factors and three levels, the proper orthogonal array $L_9$ of Taguchi method was used to design experiments of this study with the standard $L_9$ table [13] as listed in Table 5.

| Experiment no. | E     | B     | M     | F     |
|---------------|-------|-------|-------|-------|
| 1             | Level 1 | Level 1 | Level 1 | Level 1 |
| 2             | Level 1 | Level 2 | Level 2 | Level 2 |
| 3             | Level 1 | Level 3 | Level 3 | Level 3 |
| 4             | Level 2 | Level 1 | Level 2 | Level 3 |
| 5             | Level 2 | Level 2 | Level 3 | Level 1 |
| 6             | Level 2 | Level 3 | Level 1 | Level 2 |
| 7             | Level 3 | Level 1 | Level 3 | Level 2 |
| 8             | Level 3 | Level 2 | Level 1 | Level 3 |
| 9             | Level 3 | Level 3 | Level 2 | Level 1 |
Table 6 shows nine experiments were proposed conforming to the standard L₉ table. From Table 6, the mixing proportion of each mixture presented in Table 7 was calculated to conduct Proctor test in accordance with ASTM D1557 [20].

Table 6. Nine experiments used in this study

| Experiment no. | ID. mixture | E | B | M | F |
|----------------|-------------|---|---|---|---|
| 1              | C1          | 0%| 10%| 6%| 0%|
| 2              | C2          | 0%| 12%| 8%| 20%|
| 3              | C3          | 0%| 14%| 10%| 40%|
| 4              | C4          | 50%| 10%| 8%| 40%|
| 5              | C5          | 50%| 12%| 10%| 0%|
| 6              | C6          | 50%| 14%| 6%| 20%|
| 7              | C7          | 100%| 10%| 10%| 20%|
| 8              | C8          | 100%| 12%| 6%| 40%|
| 9              | C9          | 100%| 14%| 8%| 0%|

Table 7. RCCP mixing proportions (kg/m³)

| ID. mixture | Coarse aggregate | Fine aggregate | Binder | Water content |
|-------------|------------------|----------------|--------|---------------|
|             | EAF slag | Crushed stone | Cement | Fly ash |       |
| C1          | 0       | 842           | 1163   | 222.8    | 133.7 |
| C2          | 0       | 842           | 1163   | 219.2    | 182.3 |
| C3          | 0       | 842           | 1163   | 195.8    | 233.1 |
| C4          | 424     | 424           | 1172   | 134.7    | 179.6 |
| C5          | 424     | 424           | 1172   | 275.4    | 229.5 |
| C6          | 424     | 424           | 1172   | 263.1    | 140.9 |
| C7          | 867     | 0             | 1197   | 183.5    | 229.3 |
| C8          | 867     | 0             | 1197   | 169.2    | 140.8 |
| C9          | 867     | 0             | 1197   | 336.0    | 192.0 |

According to ASTM D1557, the mixture is placed five layers into the 6-in (152.4 mm) mold and compacted 56 blows of a rammer per layer (Figure 2). Each mixture is conducted with three trials to determine the average of dry density. Then, the analysis of variance (ANOVA) was applied to assess the contribution of each factor in the mixture.

Figure 2. Proctor test, (a) compacting the mixture in mold, (b) determining the density of mixture after compacting.

3. Results and Discussion
Table 8 shows the dry density of nine mix proportions determined by Proctor test. This result was analysed by Minatab software to assess the effect of four factors on the dry density of mixture. Figure 3 presents the result of the analysis of variance (ANOVA).

**Table 8.** The dry density results of RCCP (kg/m$^3$)

| ID. mixture | Trial 1 | Trial 2 | Trail 3 | Average |
|------------|---------|---------|---------|---------|
| C1         | 2235    | 2292    | 2277    | 2268    |
| C2         | 2220    | 2241    | 2250    | 2237    |
| C3         | 2107    | 2113    | 2149    | 2123    |
| C4         | 2233    | 2258    | 2262    | 2251    |
| C5         | 2255    | 2234    | 2294    | 2261    |
| C6         | 2301    | 2297    | 2308    | 2302    |
| C7         | 2244    | 2255    | 2272    | 2257    |
| C8         | 2280    | 2290    | 2276    | 2282    |
| C9         | 2381    | 2359    | 2349    | 2363    |

**Figure 3.** Analysis of Variance of the results

As can be seen in Figure 3, increasing the EAF slag as aggregate replacement in mixture led to rise the dry density. This behaviour resulted from the high-density feature of EAF slag aggregate. Whereas increasing the fly ash as cement substitution in mixture resulted in declining the dry density, because specific gravity of fly ash is lower than that of cement.

Besides, the percentage of binder in mixture hardly affected on the dry density of RCCP. Therefore, when design the mixing proportion, the mass of binder was determined by the strength requirement of RCCP.

On the other hand, the moisture content in range of 6-8% affected slightly on the dry density. And, the moisture content exceeded 8% leading the reduction of the dry density.

4. **Concluding Remarks**

Based on the experimental work, some of highlighted remarks could be drawn:

1. The higher percentage of EAF slag coarse aggregate led to the higher dry density of the mixture.
2. Increasing the fly ash content as cement substitution in the mixture led to decrease the dry density of the mixture.
3. The moisture content in range of 6-8% affected slightly on the dry density of the mixture. And, there was a dramatic reduction of the dry density when the moisture content exceeded 8%.
The percentage of binder in range of 10-14% hardly affected on the dry density of the RCCP mixture.

5. References

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