Effects of fines content and maximum particle size on mechanical properties and saturated hydraulic conductivity of recycled concrete aggregates for unbound roadbed materials in Vietnam

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ABSTRACT

Road base layers play an important role in bearing, transmitting, and distributing part of the load to the underground. Unbound aggregates crushed from natural rock are the most popular materials used to construct the base layers of the pavements. However, nowadays the sources of natural materials have been increasingly exhausted and the pollution from construction and demolition waste (CDW) is a big problem in Vietnam. Therefore, the utilization of CDW for recycling is a crucial issue to reduce the generation amount of CDW and consumption of natural resources. With regards to the applicability of recycled concrete aggregates (RCA) to unbound roadbed materials, many studies have been done to investigate the effect of grading of particles on mechanical properties. However, the effect of other factors such as maximum particle size ($D_{\text{max}}$) and fines content ($F_c$ in wt.%; typically, with particle size less than 0.075 mm) have not been fully understood. In this study, concrete waste taken from a CDW landfill in Vietnam and was crushed and sieved to prepare graded RCA samples for a series of laboratory tests to characterize mechanical properties such as compaction, bearing capacity, and saturated hydraulic conductivity. The graded RCA samples with two different $D_{\text{max}}$, 25 and 37.5 mm, and four different $F_c$ values ranging from 0 to 20 %, were prepared. This study showed that maximum dry density (MDD) and CBR value of graded aggregates with $D_{\text{max}} = 25$ and 37.5 mm reached the highest values at $F_c = 5\%$. Except for the sample with $F_c = 20\%$ and $D_{\text{max}} = 25$ mm, the measured CBR values of tested samples satisfied the technical requirements of Vietnamese and Japanese standards. Besides, the particle breakage of aggregates and saturated hydraulic conductivity were highly controlled by $F_c$ and both values decreased with increasing in $F_c$.

Keywords: road base, recycled concrete aggregate (RCA), fines content, hydraulic conductivity, particle breakage, California Bearing Ratio (CBR)

1 INTRODUCTION

1.1 CDW in Vietnam

According to the report of MONRE (2011), there were around 12.802 million tons and 22.352 million tons of solid waste discharged in Vietnam in 2008 and 2015 respectively. CDW accounted for around 10 - 15% of the total solid waste. Tuan et al. (2018) presented that approximately 2,200 apartment buildings (about 6 million m²) were built in 1970–1980, of which approximately 90% are seriously degraded and needed to be renovated or demolished. Vietnamese government issued some decrees and resolutions on renovation and reconstruction of damaged or degraded condominiums, such as Resolutions 34/2007/NQ-CP and Decree 101/2015/ND-CP, indicating that there will be a large amount of CDW discharged into the environment in future. Lockrey et al. (2016) estimated that the total amount of CDW generated in Vietnam will be 6.3 million tons and 11 million tons in 2020 and 2025 respectively. With such a large CDW being emitted, recycling of CDW is necessary to limit their impact on the environment as well as contribute to reduce consumption of natural materials. Since last few decades, the developed countries such as US, and Japan have developed technical standards for recycling CDW for the application to road construction to promote the recycling of CDW. In Vietnam, however, only 1-2% of CDW was recycled (MONRE, 2011), and in order to increase this use, it is necessary to develop the technical standards for recycled materials from CDW, but unfortunately, there is no such thing in Vietnam up to now. In order to develop technical standards of recycled materials from CDW for the road base course in Vietnam, therefore, this paper focused on effects of fines content and maximum particle size on mechanical properties of recycled concrete aggregates for unbound roadbed materials.

1.2 Literature review on effects of fines content and maximum particle size on mechanical properties of unbound roadbed materials

Gradation, quality and percentage of fines content (typically, particle size less than 0.075 mm), $F_c$ (in wt. %), affect on mechanical properties of granular materials. Oso'uli et al. (2016) studied crushed stone...
aggregates of $D_{\text{max}} = 25$ mm using three values of $F_{\text{c}}$ (5, 8, and 12 %) with two values of plastic index (5 and 9%). They reported that MDD increased with increasing in $F_{\text{c}}$. Chaulagai et al. (2017) also changed $F_{\text{c}}$ value ranging from 5-12% with two $D_{\text{max}}$ values of 25 and 50 mm. Their results showed that MDD depended on $F_{\text{c}}$ and reached the maximum value with $F_{\text{c}} = 8$ %. Besides, they also reported that the sample with $D_{\text{max}} = 50$ mm gave lower MDD value than that with $D_{\text{max}} = 25$ mm. Mishra et al. (2010) used crushed limestone and dolomite aggregates with $D_{\text{max}} = 25$ mm in their research and presented that MDD increased with increasing in $F_{\text{c}}$ in the range of 0 to 16%. Fattah et al. (2016) reported that the subbase using crushed stone with $D_{\text{max}} = 50$ mm showed the increase of MDD with increasing of $F_{\text{c}}$. Based on the previous studies, one of major trend is that MDD increase with increasing in $F_{\text{c}}$. However, an opposite trend was shown by Inan et al. (2016). They used crushed stone with $D_{\text{max}} = 37.5$ mm and indicated that MDD decreased with the increase in $F_{\text{c}}$. Besides, some researchers concluded that MDD became the highest at a certain $F_{\text{c}}$ value. Yoder et al. (1975) studied using crushed stone and gravel and showed that MDD reached the highest peak in $F_{\text{c}}$ range from 8 to 10 %. Gandara et al. (2005) demonstrated that MDD became the largest at $F_{\text{c}} = 10$ % for the tested samples with both low and high plasticity fines. Furthermore, Siswosoebrotho et al. (2005) reported that the values of MDD for subbase materials with $D_{\text{max}} = 37.5$ mm were dependent on the plasticity of fines, the highest MDD at $F_{\text{c}} = 4$ % for medium and high plasticity fines and the highest MDD at $F_{\text{c}} = 8$ % for non-plasticity fines.

With regards to the effect of fines on California Bearing Ratio (CBR), Babic et al. (2000) studied with two types of fines for base course (stone fines and clay fines) and showed that CBR increased with the increase in stone fines and CBR decreased with the increase in clay fines (in $F_{\text{c}}$ range of 0 to 10 %). Fattah et al. (2016) observed that CBR increased when stone fines increased. Inan et al. (2016) and Osouli et al. (2017) demonstrated that CBR decreased with the increase in $F_{\text{c}}$. Yoder et al. (1975) presented that the highest value of CBR was reached when $F_{\text{c}}$ values ranged from 6 to 8 %. Taherkhani et al., (2016) showed that CBR of base materials with $D_{\text{max}} = 25$ mm was attained the highest at $F_{\text{c}} = 5$ %. Siswosoebrotho et al. (2005), on the other hand, CBR reached the maximum value at $F_{\text{c}} = 5$ % with medium and high plasticity fines and reached the highest value at $F_{\text{c}} = 8$ % with non-plasticity fines. The hydraulic conductivities of road base materials are affected by fines content. For example, Babic et al. (2000) and Siswosoebrotho et al. (2005) reported that hydraulic conductivities decreased with increasing in $F_{\text{c}}$ while Taherkhani et al. (2016) showed that hydraulic conductivities of road base became the lowest with $F_{\text{c}} = 7.2$ %.

It is true that there were many studies have been carried out to examine the effects of fines on mechanical properties of unbound roadbed materials. However, most of them used natural aggregates on their studies and very limited studies for examining the effects of fines content and maximum particle size on mechanical properties and saturated hydraulic conductivity of recycled aggregates. Therefore, this study aimed to investigate the effects of fines content and maximum particle size on mechanical properties and saturated hydraulic conductivity of recycled aggregates.

Table 1. Gradation of graded RCA prescribed in TCVN 8859 (2011).

| Sieve size, mm | Graded aggregate with nominal particle size $D_{\text{max}} = 37.5$ mm | Graded aggregate with nominal particle size $D_{\text{max}} = 25$ mm |
|---------------|---------------------------------------------------------------|---------------------------------------------------------------|
| 50 | 95-100 | - |
| 25 | 58-78 | 67-83 |
| 19 | 39-59 | 49-64 |
| 9.5 | 24-39 | 34-54 |
| 4.75 | 15-30 | 25-40 |
| 2.36 | 7-19 | 12-24 |
| 0.425 | 2-12 | 2-12 |

Fig. 1. Particle size distributions of tested RCA materials in this study. (a) Tested samples with $D_{\text{max}} = 25$ mm, and (b) tested samples $D_{\text{max}} = 37.5$ mm.
Table 2. Technical requirements of aggregates used for base and subbase.

| No | Properties                           | Unit | TCVN 8859 (2011) | JRA (2010) |
|----|--------------------------------------|------|------------------|------------|
|    |                                      |      | Type I*          | Type II*   |
| 1  | Los Angeles abrasion (LA)            | %    | ≤ 35             | ≤ 40       |
| 2  | CBR at Compaction index K98         | %    | ≥ 100            | -          |
| 3  | CBR at compaction index K95         | %    | -                | ≥ 80       |
| 4  | Liquid limit (wL)                   | %    | ≤ 25             | ≤ 35       |
| 5  | Plasticity index (Ip)               | -    | ≤ 6              | ≤ 4        |
| 6  | PP index (= Ip × Passing % of 0.075mm) | -    | ≤ 45             | ≤ 60       |
| 7  | Compaction index (KC)               | %    | ≥ 98             | ≥ 98       |

* Type I is recommended for base and Type II is recommended for subbase
** Not include in Technical specification of materials. Minimum value of tested samples (Civil Engineering and Construction Management Standards. MLIT, 2016)

2 MATERIALS

Concrete waste for preparing RCA was collected at Thanh Tri CDW landfill in Hanoi, Vietnam. The concrete waste was crushed, sieved and graded in the laboratory to prepare the samples for a series of laboratory tests. The graded RCA with two different $D_{\text{max}}$, 25 and 37.5 mm, and four different $F_{\text{c}}$, 0, 5, 10 and 20 % were prepared. In this study, the gradations of graded RCA followed Vietnamese standard TCVN 8859 (2011) as given in Table 1. The particle size distributions with two different $D_{\text{max}}$ were shown in Fig. 1.

3 TEST METHODS

A series of laboratory tests was carried out to characterize mechanical properties. The tested results were compared to the technical requirements of aggregates used for base and subbase in TCVN 8859 (2011) and Japan Road Association (JRA) (2010) as shown in Table 2.

3.1 Compaction test

In order to determine the optimum moisture content, $w_{\text{opt}}$, and MDD of materials, the specimens were prepared in the laboratory satisfying the specifications followed the Modified Proctor Compaction test method in TCN 333 (2006) and JIS A 1210 (2009). Compaction tests in this study were used II-D method with weight of hammer was 4.54 kg, the dropping height is 457 mm, specimens were compacted in a cylindrical mold with diameter of 150 mm and effective height of 125 mm by using a spacer disk inserted into the mold before compaction. The specimens were divided into 5 layers; each layer was compacted with 56 blows. For each of specimens, a 5 kg of graded material was prepared and moistened with a series of moisture content.

3.2 Characteristic of particle breakage

After the compaction tests, samples were sieved to measure the mass of each particle sizes, then determined the characteristic of particle breakage. The particle breakage index was calculated by Eq. (1) following Marsal method (Marsal, 1967):

$$B_m = \sum_{n=1}^{i} \Delta p_{d_n}$$  \hspace{1cm} (1)

where $B_m$ is the particle breakage index, $\Delta p_{d_n}$ is the positive difference in percentage by weight of material retained on the $n^{th}$ sieve, when the grading before and after compaction test.

3.3 CBR test

CBR test is the most popular method to determine the bearing capacity of unbound aggregate for base and subbase of road construction in the laboratory. In this study, TCN 332 (2006) and JIS A 1211 (2009) were used to prepare the specimens (125 mm height, 150 mm inner diameter) and examine CBR tests. According the standard, each of mixtures, three specimens were prepared with a 5 kg of material that mixed with water at the optimum moisture content. Number of blows per layer was different for the three specimens, which were 10, 30, 65, respectively. After the compaction, the specimens were soaked in water for 96 hours before CBR tests. Then, the load-displacement curves for each specimen was plotted to determine the CBR values.

3.4 Saturated hydraulic conductivity test

The constant head permeability test was carried out to determine saturated hydraulic conductivity, $K_s$, of the samples following to ASTM D2434-68 (2006) and JIS A 1218 (2009). After compacting the specimens (125 mm height, 150 mm inner diameter) in the compaction test, the sample was set up as the process described in Fig. 2 to measure the quantity of water discharged during a time. Then, $K_s$ was calculated by Eq. (2):

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where \( K_s \) is saturated hydraulic conductivity (cm/s), \( Q \) is quantity of water discharged (cm³), \( L \) is the length of specimen (cm), \( A \) is cross-sectional area of specimen (cm²), \( t \) is total time of discharge (s), \( h \) is the constant head (cm).

\[
K_s = \frac{Q \times L}{A \times t \times h}
\]

(2)

4 TEST RESULTS AND DISCUSSION

The tested results were summarized in Table 3.

4.1 Results of compaction test

Figures 3a and 3b showed measured compaction curves for tested samples with four \( F_c \) values. Based on these curves, MDD and \( w_{opt} \) were determined (Table 3). As can be seen in Fig. 3, the highest MDD was appeared when \( F_c = 5\% \) for both samples with \( D_{max} = 25 \) and 37.5 mm. Compared to previous studies done with natural aggregates, RCA samples had lower MDD and MDD reached the highest peak at the lower \( F_c \) value. Besides, except for the tested sample with \( F_c = 0\% \), the samples with \( D_{max} = 37.5 \) mm had the higher MDD than that with \( D_{max} = 25 \) mm.

4.2 Particle breakage

The particle breakage of samples after compaction test were shown in Fig. 4. As can be seen from Fig. 4, the samples with \( D_{max} = 37.5 \) mm gave higher particle breakage and the values of \( B_m \) became approximately 1.2-1.3 times higher compared to those with \( D_{max} = 25 \) mm in the whole range of \( F_c \). Moreover, it is clear that the particle breakage decreased with increasing in \( F_c \) value, implying that the samples with higher \( F_c \) decrease the particle breakage due to the cushioning effect.

4.3 Results of CBR test

The results of CBR test were shown in Table 3, and the variation of CBR values as a function of dry density of samples were plotted in Fig. 5. It can be seen from Fig. 5 that the CBR increased with the increase of the dry density of materials. According to TCVN 8859 (2011), the materials used to construct road base must have the soaked CBR at K98 value is over 100%, while JRA (2010) requires that the CBR at K95 of recycled materials used for base and subbase have to be over 80% and 30%, respectively (Table 2). Compared to these requirements on CBR, it can be realized that except for the test with \( F_c = 20\% \) and \( D_{max} = 25 \) mm, the soaked CBR values of samples met the both technical requirements. In addition, the CBR values with \( F_c = 5\% \) became the highest values for both samples with \( D_{max} = 37.5 \) and 25 mm.

4.4 Results of saturated hydraulic conductivity

Fig. 6 showed the variation of measured saturated hydraulic conductivities, \( K_s \), of recycled concrete aggregates as a function of \( F_c \) values. The measured \( K_s \) values decreased monotonically with increasing \( F_c \) for both samples with \( D_{max} = 25 \) and 37.5 mm. In the range of \( F_c \) from 0 to 10%, measured \( K_s \) with \( D_{max} = 37.5 \) mm became approximately 10 times (one order) higher than those with \( D_{max} = 25 \) mm. At \( F_c = 20\% \), on the other hand, the measured \( K_s \) values became almost same for both samples. Based on these results, it can be explained that the coarser aggregates form larger pore network for water movement inside and resulted in the higher \( K_s \). And, the increase of \( F_c \) reduced the coarser pore network inside and lead the reduction in \( K_s \).

| Table 3. Summary of test results. |
|-----------------------------|---------------------|
| \( D_{max} \) (mm)          | 37.5                |
| Fines content, \( F_c \) (%)| 0  5  10  20  0  5  10  20 |
| \( w_{opt} \) (%)           | 8.8 10 11 10.6 10.5 10.4 10.3 11.6 |
| MDD (g/cm³)                 | 1.86 2.01 2.00 1.94 1.94 1.99 1.98 1.90 |
| Breakage index, \( B_m \) (%)| 73.4 60.9 47.5 41.8 53.9 42.4 39.3 30.7 |
| CBR at K95 (%)              | 81 147 133 96 118 172 99 32 |
| CBR at K98 (%)              | 116 194 169 121 189 217 189 79 |
| \( K_s \) (cm/s)            | 8.39E-04 1.74E-05 8.73E-06 4.46E-07 1.44E-04 2.50E-06 5.45E-07 5.10E-07 |
It is interesting to observe that the reduction in $K_s$ at $F_c = 20\%$ irrespective of $D_{\text{max}}$. This is probably that the water movement of tested samples at $F_c = 20\%$ was mainly controlled by fine pores inside the added fines (< 0.075 mm) and the size of aggregates did not affect significantly the saturated hydraulic conductivity.

5 CONCLUSIONS

The effects of fines content and maximum particle size on mechanical properties of recycled concrete aggregate such as compaction and bearing capacity, and saturated hydraulic conductivity were investigated in this study. Basing on the tested results, the conclusions could be presented as follows:

1. The graded RCA with $D_{\text{max}} = 37.5$ and 25 mm gave the highest MDD at $F_c = 5\%$. The particle breakage index for the tested samples with $D_{\text{max}} = 37.5$ mm became higher than that with $D_{\text{max}} = 25$ mm. The particle breakage index decreased with increasing in $F_c$ due to the cushioning effect of the added fines (< 0.075 mm).

2. The CBR values of tested samples with both $D_{\text{max}} = 37.5$ and 25 mm reached the highest values at $F_c = 5\%$. Except for the tested sample with $F_c = 20\%$ and $D_{\text{max}} = 25$ mm, the measured CBR values met the technical requirements of Vietnamese and Japanese standards.

3. The saturated hydraulic conductivity of graded RCA with $D_{\text{max}} = 37.5$ mm became higher than the samples with $D_{\text{max}} = 25$ mm in the range of $F_c$ from 0 to 10\%. The saturated hydraulic conductivity at $F_c$
was mainly controlled by fine pores inside the added fines (< 0.075 mm) and the size of aggregates did not significantly affect the saturated hydraulic conductivity.

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