Experimental Evaluation on Aggregate Particle Breakage in Unbound Granular Mixture Compaction

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Abstract: In order to evaluate the particle breakage percentage and improve fundamental understanding of particle-based mixture construction, this paper presents the laboratory testing results of mineral aggregate mix compaction. In this research, the laboratory compaction tests were conducted under heavy compaction. In preparing the testing samples, aggregate gradations, water contents, and aggregate types were considered. After compaction, CBR (California Bearing Ratio) values optimum moisture contents (OMC) or moisture content (MC) and maximum dry density (MDD) were measured. In order to quantify the particle break percentage, the compacted samples were sieved and analyzed. Furthermore after compaction the changes in gradations could be determined. Through laboratory testing results, connections with design moisture content (DMC) and actual forming moisture content (AFMC) and particle breakage with CBR (California Bearing Ratio) values were established. Besides relationship between design water content and forming water content was cubic function and proctor compaction had a great influence on gradations, particles especially coarse particles reduced a lot while fineness modulus seemed to increase and there was an optimum crushing value under which CBR reached maximum.

Key Words: Highway Engineering; Compaction; Aggregate Breakage; CBR

1. Introduction

Many researches on flexible base course have shown that graded aggregate course can effectively prevent reflection crack. However, particles may be damaged or broken during the forming process, gradation and mechanical properties may change. Studies (Einav 2007; XiLing Guo et al. 1997; Jin Meng and ZhiJong Qu 1989) have proved that particle breakage is affected by many factors. Yong Sheng Zhang et al (2015) found that particles from 13.2mm to 1.18mm were damaged and gradation changed after compaction; Miura observed internal friction angle and shearing strength decreased due to particle breakage. Ueng and Chen (2000) focused on stress-strain curve under particle broken conditions. Xiang Jun Liang et al (2003) thought that particle breakage contained main compression crushing and creep crushing. Loading time and confining pressure (Indraratna et al. 1998; Lade et al. 1996; Hua Fu et al. 2009; HanLong Liu et al. 2005) were major factors. Lade et al. (2014) suggested particle breakage was mainly due to static fatigue. Indraratna (2005) researched on loading frequency and confining pressure by tri-axial test. This paper was aimed at connecting design water content with actual forming water content,
comparing particle breakage and gradations by heavy compaction and establishing relationship between particle breakage and CBR.

2. Mineral Aggregate Gradation Design

In this research, limestone aggregates were selected and the material properties were as shown in Table 1. A total of three gradations were designed as listed in Table 2 where the gradation1, gradation2, and gradation3 are a coarse-grain gradation. The maximum particle sizes are 26.5mm for gradation1 and 31.5mm for the other two gradations.

Table 1. Raw material density.

| Diameter of particle | 26.5 | 19 | 16 | 13.2 | 9.5 | 4.75 |
|----------------------|------|----|----|------|-----|------|
| Apparent density     | 2.762| 2.766| 2.764| 2.780| 2.812| 2.826|
| Table dry density    | 2.719| 2.732| 2.744| 2.755| 2.784| 2.804|
| Bulk density         | 2.695| 2.712| 2.733| 2.741| 2.769| 2.792|

Table 2. Experimental gradations.

| Grain size | 31.5 | 26.5 | 19.0 | 16.0 | 13.2 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Gradation1 | 100.0| 97.9 | 84.7 | 79.7 | 71.9 | 60.1 | 47.7 | 36.5 | 22.7 | 13.6 | 4.6  | 1.4  | 0.1  |
| Gradation2 | 98.7 | 94.7 | 80.1 | 71.5 | 63.8 | 50.9 | 43.7 | 32.8 | 16.1 | 10.8 | 4.5  | 1.7  | 0.1  |
| Gradation3 | 93.5 | 88.3 | 74.4 | 65.3 | 57.6 | 43.7 | 24.9 | 16.5 | 13.0 | 9.5  | 3.3  | 0.8  | 0.1  |

3. Optimum Water Content and Maximum Dry Density

The inner diameter of compaction cylinder is 150mm and 120mm in height. During the experiment, materials must be filled in three layers, each layer should be compacted 98 times, each gradation forms five specimens then optimum water content and maximum dry density should be determined. Results are shown in Table3.
Table 3. Optimum water content and maximum dry density.

|                | Gradation1 | Gradation2 | Gradation3 |
|----------------|------------|------------|------------|
| OMC (%)        | 5.8        | 3.8        | 4.4        |
| MDD (g/cm³)    | 2.250      | 2.191      | 2.238      |

4. Design water contents versus water contents in compacted samples

During the mixture compaction, the internal water came out and appeared on the top of the mixture specimen due to the internal pressure induced by the compaction force. Therefore, the water contents determined in the mix proportion design phase are different from those water contents of the specimens after compaction. In order to more accurately determine the max density which is closely related to the optimum water content, the water loss during the compaction should be evaluated. Under this background, this research performed a series of tests to build the links between the design water contents and the actual water contacts of the compacted specimens. The testing results are shown in Table 4 and plotted in Figure 2.

Table 4. Design water content and actual forming water content.

| Gradation1   | DMC (%) | 4  | 5  | 6  | 7  | 8  | 10 |
|--------------|---------|----|----|----|----|----|----|
| AFMC (%)     | 3.8     | 4.9| 5.6| 5.7| 5.8| 5.9|
| Gradation2   | DMC (%) | 3  | 4  | 5  | 6  | 7  |
| AFMC (%)     | 2.8     | 3.5| 3.7| 3.8| 4.2|
| Gradation3   | DMC (%) | 3  | 4  | 5  | 6  | 7  |
| AFMC (%)     | 2.8     | 3.6| 4.3| 4.5| 4.7|

Figure 2. Design moisture and actual forming moisture.

From Figure 2, it can be observed that much more water was required in order to
achieve MDD in finer specimens, which may have something to do with fine aggregate content. On the one hand fine aggregates have a lubricating effect that arises from many fine particles in the mixture on the other fine aggregates have larger surface areas and have a strong ability of adsorption to water, from this point finer gradation should have a higher OMC. The results were affected by two factors together. While the coarser gradations have smaller surface area and higher void, therefor water in the specimen can’t be maintained easily. These may explain why gradation1 has a higher OMC than the other two gradations. During the compaction progress the finer specimen would not accept additional water and the excessive water became standing water on the top of the specimens.

As for DMC and AFMC, it shows a cubic function between them. For gradation1 the equation is $y=0.0302x^3-0.7335x^2+5.9107x-10.002$, gradation2 is $y=0.0747x^3-1.1578x^2+6.04x-6.8661$ and equation of gradation3 is $y=0.0054x^3-0.217x^2+2.237x-2.0694$. Through these three equations, connections between DMC and AFMC were established.

5. Gradation impact on aggregate breakage

In order to describe the aggregate breakage between different gradations, $B_g$ is adopted, which was once used to evaluate rock-fill of Mica Dam by Marsa (YuFeng Gao et al. 2009) and $B_g$ should be the total reductions of each file aggregate, the formula is described as formula (1) and the results are listed in Table 5.

$$B_g = \sum \Delta W_{ki} - \sum \Delta W_{kf}$$  \hspace{1cm} (1)

$\Delta W_{ki}$—material content of each file before compaction

$\Delta W_{kf}$—material content of each file after compaction

|         | OMC (%) | MDD (%) | $B_g$ |
|---------|---------|---------|-------|
| Gradation1 | 5.8     | 2.25    | 5.69  |
| Gradation2 | 3.8     | 2.191   | 6.25  |
| Gradation3 | 4.4     | 2.238   | 6.18  |

Compared to gradation1 and gradation2, gradation1 crushed less and this may have something to do with fine aggregate content. The fine aggregate content of gradation1 comes up to 47.7% however, gradation2 is 24.9% and gradation3 fine aggregate content is 34.7%. For gradation1, the coarse aggregates were suspended in fine aggregates and particles could move easily so the pressure between particles was low. However gradation2 and gradation3 had more coarse aggregates and particles were close to each other, when compacted, the particles squeezed and particles could hardly move; besides studies have shown that confining pressure for coarser gradation is higher than finer gradation so the particles of coarser gradation was under high stress condition. Besides it is clear that fine aggregates have larger surface area and a strong ability to water absorption, both of these provide a lubrication effect on large particles and the stress conditions for finer gradations is lower than coarser gradations.
Furthermore they can provide much more coordination and contract point which could reduce the pressure because of these factors, single particle bears lower pressure.

6. Influence on gradation by heavy compaction

The gradation always changes a lot after heavy compaction. However, there is no index to evaluate but we always use fineness modulus to evaluate the degree of thickness of fine aggregate and the fineness modulus is lager, the more coarse aggregate is. Formula is described as (2) and results are listed in Table 7. As for coarse aggregate, we use reduction of each file to evaluate the change degree and the results are placed in Table 6, besides the gradations are shown in Figure 3 after compaction.

\[
M_f = \frac{(A_{2.36} + A_{1.18} + A_{0.6} + A_{0.3} + A_{0.15}) - 5 \cdot A_{4.75}}{100 - A_{4.75}}
\]  

(2)

\(M_f\)—fineness modulus;

\(A_{4.75}, A_{2.36}…A_{0.15}\)—Cumulative sieve percentage of each sieve pore

Table 6. Reduction of coarse aggregates of each gradation.

| Gradation1 | Water content (%) | 3.85 | 4.93 | 5.65 | 5.72 | 5.80 | 5.93 |
|------------|-------------------|------|------|------|------|------|------|
|            | Change value      | -1.48| -1.95| -1.27| -1.48| -1.34| -1.87|
| Gradation2 | Water content (%) | 2.85 | 3.55 | 3.72 | 3.83 | 4.30 |      |
|            | Change value      | -4.20| -4.75| -3.38| -3.71| -2.63|      |
| Gradation3 | Water content (%) | 2.81 | 3.65 | 4.37 | 4.58 | 4.72 |      |
|            | Change value      | -4.05| -3.83| -3.95| -4.27| -4.64|      |

Table 7. Fineness modulus.

| Gradation1 | Water content (%) | 3.85 | 4.93 | 5.65 | 5.72 | 5.80 | 5.93 | Natural gradation |
|------------|-------------------|------|------|------|------|------|------|-------------------|
|            | Fineness modulus  | 3.03 | 3.04 | 2.99 | 3.08 | 3.07 | 3.08 | 3.35              |
| Gradation2 | Water content (%) | 2.85 | 3.55 | 3.72 | 3.83 | 4.30 |      | Natural gradation |
|            | Fineness modulus  | 3.04 | 3.05 | 3.07 | 3.10 | 3.08 |      | 3.27              |
| Gradation3 | Water content (%) | 2.81 | 3.65 | 4.37 | 4.58 | 4.72 |      | Natural gradation |
|            | Fineness modulus  | 3.14 | 3.17 | 3.22 | 3.17 | 2.60 |      | 3.39              |
Figure 3. Restore gradations under optimum water content after heavy compaction.

All gradation curves rose and coarse aggregates reduced while fine aggregates increased. Overall, gradation1 changed least, gradation2 changed most and gradation3 was between them. In gradation1, 26.5mm, 19mm and 13.2mm changed most, for example, 26.5mm decreased 72.8%, however mineral fillers increased from 0.1% to 3.58%. In gradation2, 31.5mm, 16mm and 9.5mm reduced most, 31.5mm decreased by 58.5%, 0.075mm increased by 82.8% and mineral fillers increased from 0.1% to 2.45%. In gradation3, 26.5mm, 19mm, 16mm reduced a lot, 26.5mm and 19mm reduced by 47% and 25% but 4.75mm, 2.36mm, 1.18mm and mineral fillers increased. Obviously mineral fillers increased from 0.1% to 3.55%, it’s clear that 31.5mm, 26.5mm, 0.075mm and mineral fillers changed most while other file aggregates seemed to change less.

After compaction coarse aggregates tended to decrease, in specific the coarse aggregate content of gradation1 decreased by 1.5%, gradation2 decreased by 3.74% and gradation4 decreased by 4.15%. As for fineness modulus, gradation1 was 3.05 after heavy compaction, however the original was 3.35, gradation2 changes from 3.27 to 3.07 and gradation3 changes from 3.39 to 3.06. From all mentioned above, heavy compaction has a great influence on natural gradation.

7. Influence of particle breakage on CBR

CBR (California Bearing Ratio) is an important index for graded crushed stone design, which reflects the ability to resist partial load (XiLing Guo et al. 1997) and is tested in accordance with "JTG + E40-2007" (The ministry of communications highway research institute 2007) road soil test procedures’ execution. The equipment includes compaction cylinder and penetration staff, the diameter of penetration staff is 50mm and 100mm in length. Besides, if the result of 2.5mm penetration is less than 5mm’s we need to redo, if the test result is still the same, we use CBR of 5mm penetration as the final value. The relation between CBR and crushing value is shown in Table 9.
Table 9. Relation between CBR and crushing value.

| Gradation | Bg  | CBR  |
|-----------|-----|------|
| Gradation1 | 6.31 | 91.94 |
| Gradation2 | 8.19 | 145.51 |
| Gradation3 | 6.30 | 146.33 |

Similar to the soil compaction test, there is an optimum crushing value under which CBR reaches the maximum, the reasons may be as follows, first of all when coarse particle broken, there will be more mineral fillings and the void will be filled by these mineral fillings, which makes specimen much denser. Besides, skeleton dense structure can form more easily. Furthermore, aggregates’ crushing increase the number of contact points between the skeleton and reduces large particle contact force contribution rate, therefore skeleton dense structure enforced further. At last under optimum crushing value, Specimen becomes much denser and the role of the skeleton has been further enhanced and resistance to deformation has been further improved.

Summary

Due to the local excessive particle interlocking forces, aggregates may be broken and the original gradations are altered as a result. This paper has presented a series of laboratory tests for evaluating various factors which may give effects on aggregate breakages. Through this research, the following findings were observed:

(1) The crushing value between different gradation types was different, Usually skeleton dense structure crushed more than suspended dense structure and particle breakage is related to fine aggregate content, besides aggregate gradations were significantly influenced, the coarse aggregate percentages of 31.5mm, 26.5mm and 19mm decreased while 0.15mm, 0.075mm, and mineral fillers increased;

(2) There is an optimum crushing value under which CBR reaches the maximum value;
(3) Relationship between actual forming water content and design water content can be described by cubic function.

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REFERENCES

Einav, I. (2007). "Breakage mechanics—Part I: Theory." Journal of the Mechanics & Physics of Solids, 55(6), 1274-1297.
Indraratna, B. (2005). "Effect of confining pressure on the degradation of ballast under cyclic loading." Geotechnique, 55(4), 325-328.
Indraratna, B., Ionescu, D., and Christie, H. D. (1998). "Shear Behaviour of Railway Ballast based on Large Scale Triaxial Testing." Faculty of Engineering Papers.
Lade, P. V., Karimpour, H., Lade, P. V., and Karimpour, H. (2014). "Static Fatigue Produces Time Effects in Granular Materials." American Society of Civil Engineers(365), 530-539.
Lade, P. V., Yamamuro, J. A., and Bopp, P. A. (1996). "Significance of Particle Crushing in Granular Materials." American Society of Civil Engineers, 122(4), 309-316.
Ueng, T. S., and Chen, T. J. (2000). "Energy aspects of particle breakage in drained shear of sands." Géotechnique, 50(1), 65-72.
HuaFu, HuaLing, and ZhengYin Cai. (2009). "Experimental study on the soil particle coarse particle crushing impact factors." Journal of Hohai University (Natural Sciences (01), 75-79.
YuFeng Gao, BingZhang, WeiLiu, and YanMei Ai. (2009). "The characteristics of rockfill particle breaking large triaxial test study." Rock and Soil Mechanics, 30(5), 1237-1240.
XiLing Guo, HuiHu, and ChengBaoGang. (1997). "The dilatancy of rockfill particle breaking and the influence of shear strength." Geotechnical Engineering(03), 86-91.
The ministry of communications highway research institute. (2007). JTG E40-2007 highway geotechnical test procedures, the people's traffic.
JunLiang, HanLong Liu, and HanLong Liu. (2003). "Pile of rock creep mechanism analysis and particle breakage characteristics research." Rock and Soil Mechanics(03), 479-483.
HanaLong Liu, HongYu Qin, YuGao Feng, and YunDong Zhou. (2005). "Experimental study of coarse aggregate particle breakage." Rock and Soil Mechanics(04), 562-566.
JinMeng, and ZhiJongQu. (1989). "Particle breakage of moraine soil under high pressure and stress strain relations." Journal of Sichuan University (Engineering
YongSheng Zhang, XiaoMing Huang, ShuTao Meng, and FeiTian. (2015). "The influence of different forming methods of grading macadam." Highway and Transportation Research and Development(09), 32-35.