Improved Mechanical Properties of Asphalt Mixture Using Vacuum Compaction Method

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Abstract. A novel vacuum compaction method, aiming to improve mechanical properties of asphalt pavement, was developed and compared to common compaction method. A compaction cylinder with a hole of adjusting air pressure was designed and fabricated and was utilized for finishing vacuum compaction and common compaction. Compared common compaction, at vacuum degree of -0.04 MPa air void of the sample after compaction decreases by 6.25% and at vacuum degree of -0.08 MPa it decreases by 10.9%, which indicated that vacuum compaction is more efficient than common compaction. Similarly, the changing of voids in mineral aggregate also exhibited the same trend, which indicated that vacuum degree at -0.08 MPa is the most efficient value. Through splitting test, splitting strength under vacuum compaction was higher than that under common compaction, by 10.2%. Furthermore, the ability of strain-stress increased by 11.55% by applying vacuum compaction. These results prove that the mechanical properties of asphalt pavement were optimized by the use of vacuum compaction instead of common compaction.

Keywords: Vacuum compaction, Asphalt mixture, Mechanical properties, Splitting strength, Air void.

1. Introduction
Compaction is a crucial process, known to influence significantly the performance of asphalt pavement [1-3]. Asphalt mixtures that exhibit a good compaction performance can be compressed easily to the design volume requirements as to maintain a certain level of stability and thus become suitable for road use [4-6]. The contemporary increase in highway construction and the high standards of construction quality, improvement of the mechanical properties of asphalt pavement has become imperative.

Many researchers have attended to mixture design and compaction method as parameters that -if optimized - can improve the mechanical properties of asphalt pavement [7-9]. Previous studies indicated that mixture design affects positively the mechanical properties of asphalt pavement, thus, this parameter will continue to play a key role in the future. However, all asphalt mixtures ultimately require to be compacted in terms of achieving the desirable performance. The effect of compaction methods using gyratory and vibratory equipment on the aggregate orientation within asphalt mixtures has also been studied [10]. Jiang et al. studied compaction mechanical properties of optimal asphalt–aggregate ratio, using different compaction methods and proved that vertical vibration compaction method (VVCM) is an effective method for the improvement of mechanical properties of asphalt.
pavement [11]. Faheem and Bahia [12] studied the compaction characteristics of hot mix asphalt, using a Gyratory Plate Load Assembly and a Superpave Gyratory Compactor. Recently, double-frequency composed vibration was developed and was used to design a vibratory roller [13-14]. This was able to excite simultaneously two frequency components, which was more effective than traditional vibration compaction. However, when the compaction degree reached a higher extent, free gas would reduce, leaving only the gas enclosed in the pores of the mixture, which wrapped by the asphalt would form gas springs which will resist plastic deformation of the asphalt mixture [15-16]. Resolving this problem is imperative, and it needs new improving compaction technology.

In this paper, a novel vacuum compaction method was developed. A compaction device with a hole of adjusting air pressure was designed and fabricated. A compaction device implemented separately common and vacuum compaction methods. Finally, the mechanical properties of the asphalt mixture after these two different compaction methods were compared.

2. Experimental Procedure
In current experimental procedure, the asphalt (A70) including high viscosity and softening point was selected. The asphalt mixture pavement also adopted identical ratio to AC13, as presented in table 1. The slag powder and asphalt used was measured 6 wt.% and 5 wt.%, respectively.

Table 1. The gradation of AC13.

| Aggregate ratio (mm) | 13.2-16 | 9.5-13.2 | 4.75-9.5 | 2.36-4.75 | 1.18-2.36 | 0.6-1.18 | 0.3-0.6 | 0.15-0.3 | 0.075-0.15 |
|---------------------|---------|----------|----------|-----------|-----------|---------|---------|---------|-----------|
| Percentage          | 5%      | 18.5%    | 23.5%    | 16%       | 10.5%     | 7.5%    | 5.5%    | 3.5%    | 4%        |

The aggregates were initially dried by using an electric drying machine. The mass of each type of aggregate was determined according to the ratio of the aggregates. Additionally, the mass of asphalt according to the ratio of asphalt mixture was determined, by heating it to 160 °C. Subsequently, the asphalt, the slag powder and the dried aggregates were mixed and stirred and finally the asphalt mixture was obtained.

Both common and vacuum compaction methods were carried out in a compaction cylinder, as presented in figure 1, Hammer’s weight was 4.536 Kg, its cavity diameter was 101.7 mm and its dropping height equaled 450mm throughout the experimental procedure. Its operational principle was as follows: The air in the vacuum compaction cavity was extracted in advance to gradually adjust the vacuum degree and retain it stable when the vacuum degree required a certain level. Subsequently, the hammer was lifted by hand operation at the initial maximum height, assuring the same drop height at each time. The hammer will bear the free falling gravity, namely acted on the asphalt mixture of the cavity, which achieves to compact the asphalt mixture in a vacuum environment. To ensure the accuracy of the experiment, both the vacuum hammer and stirring devices could be initially preheated to 165 °C. The height between the top cover of the compaction hammer and the top cover of the device was measured by a Vernier caliper, which ensures the same measuring reference surface during each experimental procedure.

Figure 1. Vacuum compaction cylinder.
In the experiment, the total compacting times were 150. Subsequently this procedure, compaction air void and voids in mineral aggregate of asphalt pavement, were measured by Surface-dry Condition Method [17]. Finally, splitting test of asphalt pavement under the common and the vacuum compaction was conducted by using the Electro-hydraulic Servo Fatigue Testing Machine.

3. Results and Discussion
Table 2 presents compaction performance under five different kinds of compaction states (1-normal air pressure, 2-vacuum degree at -0.04 Mpa, 3-vacuum degree at -0.06 Mpa, 4-vacuum degree at -0.08 Mpa, 5-vacuum degree at -0.09 Mpa). According to the air void and voids in mineral aggregate obtained by Surface-dry Condition Method, in figure 2, the change of the performance of the air void and voids in mineral aggregate was drawn, under different compaction states.

Table 2. Compaction performances under five kinds of compaction states.

| No. | Diameter(mm) | Average height (mm) | mass in air (g) | mass in water (g) | surface-dry mass (g) | theoretical density (g/cm$^3$) | air void | voids in mineral aggregate |
|-----|--------------|---------------------|-----------------|-------------------|----------------------|--------------------------------|----------|---------------------------|
| 1   | 101.7        | 65.0                | 1147.7          | 685.2             | 1195.5               | 2.369                          | 5.1      | 15.80                     |
| 2   | 101.7        | 64.6                | 1136.7          | 678.7             | 1182.8               | 2.369                          | 4.8      | 15.54                     |
| 3   | 101.7        | 64.7                | 1129.6          | 673.8             | 1170.1               | 2.369                          | 4.7      | 15.45                     |
| 4   | 101.7        | 64.2                | 1121.4          | 683.5             | 1179.6               | 2.369                          | 4.6      | 15.36                     |
| 5   | 101.7        | 64.4                | 1132.0          | 675.9             | 1177.2               | 2.369                          | 4.7      | 15.45                     |

According to figure 2, it was pronounced that, by increasing the vacuum degree, air void and voids in mineral aggregate of samples first decrease and then increase, reaching the minimum value of air void and voids in mineral aggregate for 4# sample, corresponding to vacuum degree at -0.08 Mpa, which show that the effect of vacuum compaction is better than that of common compaction. By comparison of common compaction, at a vacuum degree of -0.04 Mpa, air void of the sample after compaction decreases by 6.25%, and at a higher vacuum degree (-0.08 Mpa) it decreases by 10.9%. Similarly, the changing of voids in mineral aggregate also presents the same trend. For vacuum compaction, these results indicate that vacuum degree at -0.08 MP are presents the most efficient value.

![Figure 2. Air void and voids in mineral aggregate under different compaction conditions.](image-url)
According to these results, to study the influence of vacuum compaction on mechanical properties of asphalt mixture, the compaction properties under common and vacuum compaction at a vacuum degree of -0.08 Mpa were compared. Split tests were utilized to measure the mechanical properties of asphalt mixture, as illustrated in figure 3. The width of load strip was 12.7 mm and the radius of samples equaled 50.8 mm.

Figure 3. the process of asphalt samples.

Figure 4, illustrates bearing load state of asphalt pavement samples under two different compaction states. Figure 5, presents strain-stress performance of asphalt pavement samples under two compaction states. According to figure 4, during 1-7s stage, bearing load capacity of two kinds of samples was approximately identical, since the force load increases constantly, while it was limited during the earlier stage. By time, the force load in the two kinds of samples gradually increased and initially their bearing load capacity suddenly increased, then smoothly changed and finally it decreased. By comparison of their bearing load capacity, the samples under vacuum compaction were higher than that under common compaction, reaching the maximum force load of 10.844 kN during vacuum compaction and the minimum force load of 9.840 kN during common compaction. Above-mentioned results demonstrate that splitting strength under vacuum compaction was higher compared to common compaction, increasing by 10.2%. Moreover, the samples through vacuum compaction were still able to bear more force when they have been cracked. According to figure 5, the changing trend of strain-stress and bearing load was almost consistent. By comparison of their bearing load capacity, the samples under vacuum compaction were higher than that under common compaction, reaching the maximum force load of 1.062 MPa in vacuum compaction and the minimum force loaded of 0.952 MPa in common compaction, increasing by 11.55%. The results of split test proved that mechanical properties of asphalt pavement using vacuum compaction were improved compared to that using common compaction.
Figure 4. bearing load of two kinds of samples.  

Figure 5. strain-stress of two kinds of samples.

Compared with common compaction, vacuum compaction achieved better compacting effect, due to the different compaction mechanism. During the process of asphalt mixture, spreading and compacting, particles of aggregates were close to each other. This resulted in squeezing forces, which compressed the gas that was enclosed in the pores and the cracks. The pressure formed by the gas closed in the pores was higher than environmental air pressure due to the effect of internal gas compression, since the mechanical performance of these gases were similar to that of the rock. The gases in the pores of the asphalt mixture are separated in two kinds of states: (1) The gas of the pore had been compressed and gas pressure existed; (2) The gas of the pores had not been compressed and gas pressure was similar to the air pressure, as illustrated in figure 5.

It was assumed that the other components of the mixture constitute a continuous homogeneous medium with linear elastic properties, except the gas in the pores. Considering the internal ordinary direction of the pore as the forward direction, in figure 6a and figure 6b, the $\Delta \sigma$ force simultaneously acted on both the outer surface of the asphalt mixture and the inner surface of the pore in the first group. The total volume change of the pores and the asphalt mixture was $\Delta V_0$. In the second group, the force $\Delta \sigma$ only acted on the outer surface of the asphalt mixture and the total volume change of the pores and asphalt mixture were $\Delta V_d$ and $\Delta V_p$, respectively. According to Betti reciprocal theorem, authors obtained the following formula:

$$\Delta \sigma \times \Delta V_d - \Delta \sigma \times \Delta V_p = \Delta \sigma \times \Delta V_0$$  \hspace{1cm} (1)

$\Delta \sigma$—stress change of asphalt mixture and pore, MPa;
$\Delta V_d$—the change of the total volume of the asphalt mixture in figure b, m$^3$;
$\Delta V_p$—volume change of the pores in figure 5b, m$^3$;
$\Delta V_0$—total volume change of asphalt mixture in figure a, m$^3$. 

Figure 6. Pore state of asphalt mixture.
Therefore, during the process of the vacuum compaction, various kinds of pores of asphalt mixture, which had been pressed initially, would be accelerated compression under around the pressure reduced. Moreover, this additional pressure could squeeze and break the pores that were in balance, which would increase the compaction depth of asphalt mixture and the pavement compaction degree, while reducing the pore quantity.

4. Conclusions
In current paper, a novel vacuum compaction method was presented to improve the mechanical properties of asphalt pavement. This method was utilized to carry out both common and vacuum compaction. The experimental results demonstrate that, at vacuum degree of 0.04 Mpa, air void of the samples after compaction decreases by 6.25% and at vacuum degree of 0.08 Mpa it decreases by 10.9%. Similarly, the changing of voids in mineral aggregate also presents the same trend, which indicates that the effect of vacuum compaction was more efficient than that of common compaction, while vacuum degree at -0.08 MPa was the optimal value. By comparison of their bearing load capacity, the samples under vacuum compaction presented higher capacity than that under common compaction, by reaching the maximum force load of 10.844 kN during vacuum compaction and the minimum force load of 9.840 kN during common compaction (10.2% increase). Furthermore, the ability of strain-stress increased by 11.55%. Above-mentioned results indicate that vacuum compaction method can effectively improve mechanical properties of asphalt pavement, which provides a novel method for the enhancement of the road quality and lifespan.

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