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TECHNICAL NOTE

Investigating the Effect of Compaction Level and Aggregate Grading of Stone Materials in Base Layer on Bitumen Penetration Rate

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ABSTRACT: One of the layers that is applied on the base layer in asphalt pavements and increases the cohesion between the two layers, is the prime coat layer. Due to the fact that there are usually problems with the prime coat penetration into the base layer and penetration is not usually done well, there is a need to identify the factors affecting the penetration into the base layer. In this study, the penetration rate of prime coat coatings made of emulsified bitumen CSS-1h on the grain base level with different aggregate grading (aggregation close to the lower, middle and upper limits in two different types of aggregate grading) and different compaction levels were examined. Optimum water content, density, California Bearing Ratio (CBR) and the permeability of the samples were also examined. According to the results, the compressive strength of stone materials samples increases with approaching the upper limit (fine grain) and increasing the compaction. Also, increasing the grain size and decreasing compaction, increases the prime coat penetration rate, so that the 90% compacted sample with aggregate grading Type 3 has the highest penetration rate. The effect of moisture is obvious on the prime coat penetration, so that prime coat penetration rate is greatly reduced in saturation mode, but moisture in the base layer can help the prime coat to penetrate into the base layer.

Keywords: Aggregate Grading, Base Layer, Compaction, Emulsified Bitumen, Penetration, Prime Coat.

1. Introduction

Iran, like many other countries, uses asphalt pavement. Due to the scarcity of oil resources and environmental protection, the preservation of asphalt layers reduces environmental and economic concerns. One of the approaches to increase the life of asphalt pavements is to improve their engineering performance. (Taherkhani, 2016). In general, The structure of asphalt pavement is a multilayer system (Zhang et al., 2017) and the stress-strain division of the pavement is related to the property of the bonding interface. (Bastidas-Martínez et al., 2020; Hu et al., 2017). Asphalt mixtures

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are usually used in the upper layers of flexible pavements and the protection of the underlying layers against traffic loads and environmental conditions as well as creating a quality surface is one of the most important tasks of asphalt mixtures. (Taherkhani and Afroozi, 2017). Among the pavement layers, the base layer plays an important role in the expression of pavement performance. This layer has a significant role in the distribution of the applied load from the surface to the subgrade layer, so that the transferred stress to the sub-base and subgrade layer reduces (Huang, 2004). Therefore, this layer must have high resistance. Materials aggregate grading is one of the most important factors that affects its resistance and compressive strength (Chhorn and Lee, 2018; Šernas et al., 2020; Xu et al., 2018), and for this reason, different standard aggregate grading are defined in pavement standards regulations for different types of base layers. These aggregate grading are determined by several factors, such as the type of pavement, the type and location of the desired layer in the pavement system, the thickness of the layer and the size of the maximum aggregate diameter (AASHTO, 2013).

To prepare and spread the asphalt layer on the base layer, a layer of bitumen with low viscosity is distributed on the base surface, which is called prime coat (Cross et al., 2005). Distributed bitumen penetrates into the pores of stone materials, and it will facilitate the cohesion of the asphalt layer to the materials under, as well as integrating and consolidating the materials. It also isolates the base layer and binds loose aggregates to each other, providing a uniform surface so that its status does not change during asphalt paving (Chun et al., 2017; Ouyang et al., 2020). Due to the environmental harms of cut-back bitumen, emulsified bitumen is usually used to apply this layer (Slaughter, 2004). Emulsified asphalt is selected with different de-emulsification speed, different viscosity and different asphalt content according to different types of base (Wang et al., 2017). Due to the importance of the aggregate grading in the base layer and the role of the prime coat in the proper performance of the pavement layer, there is a need for research on the factors affecting the penetration and diffusion of the prime coat layer.

Research and publications in the field of the prime coat has been summarized to a limited number of researches, most of which express its methods and practical points. In these researches, little investigations have been done on the factors affecting the penetration of the prime coat. In this context, the instructions provided by Cross and Shrestha (2005) for single coat and prime coat layers investigated how and when to use these bitumen layers, especially when you need to use prime coat layer, and expressed the types and extent of used materials. One of the significant results has been the importance of proper penetration of the prime coat in creating high performance (Cross et al., 2005). Mohan et al. investigated the penetration rate and cohesion resistance of different types of prime coats on the grain basis. In this research, broken limestone materials were used to construct the base layer, afterwards bitumen was added to the layer in two fashions of spraying and mixing to evaluate the effect of bitumen distribution type. After the experiments, they stated that the best prime coat among the used prime coats were Terra Prime and MC-30 (Mohan et al., 2013). The National Institute for Transport and Road Research (NITRR) states that due to the importance of the prime coat penetration, the prime coat must be able to wet and penetrate the soil layer on the grain basis and create a layer with high cohesion on the basis. Also, the penetration depth depends on the base layer compaction, and the higher the compaction, the lower the penetration rate (Freeman et al., 2010). Furthermore, according to Vignarajah et al. (2007)'s research, prime coat penetration into the base layer depends on various factors such as the prime coat implementation method, bitumen type, base layer materials, construction method, base layer implementation and base layer permeability. Also, Mantilla and Button (1994) examined the permeability of two types of MC-30 soluble bitumen and two types of emulsified bitumen in different water contents, which showed the penetration rate to be higher than 5 mm in all cases and the two soluble bitumen had the highest penetration rate. Furthermore, Ishai and Livneh (1984) noted less penetration of emulsified bitumen comparing to soluble bitumen, however, the penetration rate of emulsified bitumen was satisfactory. Kucharek et al. (2008) conducted some researches on solvent-free emulsified bitumen and their permeability into grain materials. After making several samples of solvent-free emulsified bitumen, they conducted some experiments such as modified sand penetration tests to evaluate the duration and depth of emulsified bitumen penetration into grain materials with different aggregate grading, compaction levels and moisture values. Finally, the best formulation for making emulsions was reported according to their permeability.

Ouyang et al. (2020) made solvent-free emulsified bitumen, using changes in emulsified bitumen components (such as emulsifiers, bitumen and wetting agents) that affect the particle size of emulsified bitumen and its viscosity, and examined their penetration into the base layer. The results of their experiments have shown that adding wetting agents to the emulsified bitumen can greatly increase the penetration depth of bitumen, and adding emulsifiers will reduce the particle size, which can improve the permeability of the emulsified bitumen.

In this study, which was conducted to investigate the effect of aggregate grading and compaction of the base layer on the emulsified bitumen penetration, firstly, by conducting various experiments, rock mixtures characteristics (optimum water percentage, density, California Bearing Ratio (CBR), and permeability) prepared by two types of aggregate grading as stated in AASHTO Guidance (Transportation Officials, 1993) for stone base layers (aggregate grading Types 3 and 4) is obtained in three aggregate grading limits (lower, middle, upper) and finally the emulsified bitumen absorption rate is investigated in samples made.

2. Materials and Methods

2.1. Materials

The aggregates used to make the base layer samples were limestone aggregates, which are commonly used in pavement layers construction (Behbahani et al., 2020; Motamedi et al., 2021). The bitumen used for the prime coat was slow setting emulsified bitumen CSS-1h, the characteristics of which are given in Table 1. The samples required for the experiments were made according to the aggregate grading shown in Table 2 and Figures 1 and 2.

Table 1. Characteristics of the emulsified Bitumen used for prime coat

No.	Tests title		Standard range		Result	Tests method
			Min	Max		
1	Say bolt viscosity at 25°C, (s)		20	100	**20**	ASTM D88/ISIRI20644
2	Say bolt viscosity at 50°C, (s)		20	100		ASTM D88/ISIRI20644
3	Storage stability		--	0.1	**0.05**	ASTM D6930/ISIRI 20637
4	Sieve test		--	0.1	**0.03**	ASTM D6933/ISIRI20638
5	Cement mixing of emulsified bitumen (%)		--	2	**1**	ASTM D244 /ISIRI 13581
6	Residue by distillation (%)		57	--	**62**	ASTM D6997/ISIRI13580
7	Particle charge		Cationic/Anionic		**Cationic**	ASTM D244/ISIRI3580
8	Test on residue after TFOT	Penetration, 0.1 mm, @25 °C	100	250	**120**	ASTM D5/ISIRI 2950
9		Ductility, cm, @25 °C	40	--	**110**	ASTM D113/ISIRI 3866
10		Solubility in TCE wt (%)	97.5	--	**98.7**	ASTM D2042/ISIRI 2953

Table 2. Standard limit for base layer for aggregate curve

Sieve size (mm)	Passing (%)	
	Type III	**Type IV**
50	100	--
37.5	--	100
25	75-95	70-100
19	--	60-90
9.5	40-75	45-75
4.75 (#4)	30-60	30-60
2 (#10)	20-45	20-50
0.425 (#40)	15-30	10-30
0.075 (#200)	2-8	2-8

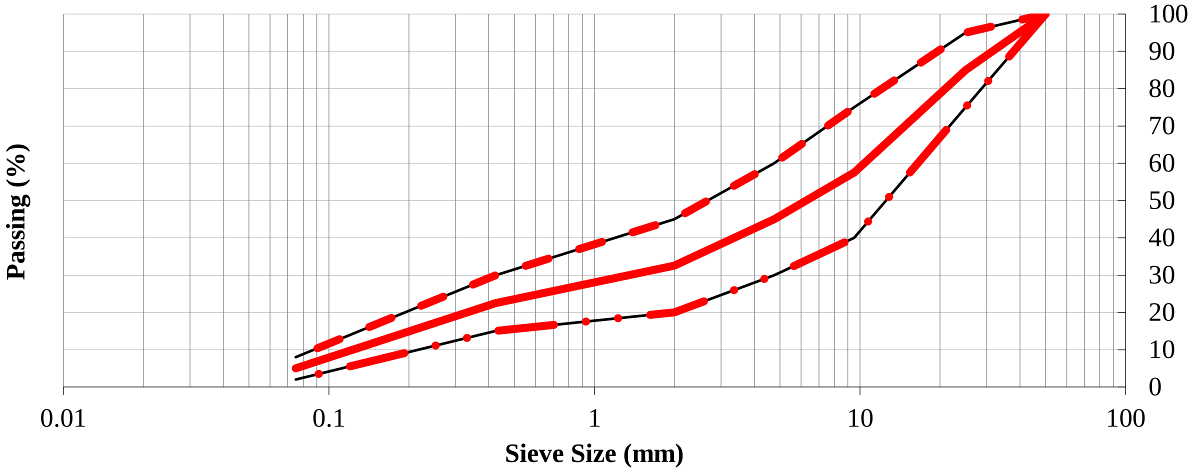


Fig. 1. Aggregation diagram Type 3 (lower, middle, upper limits)

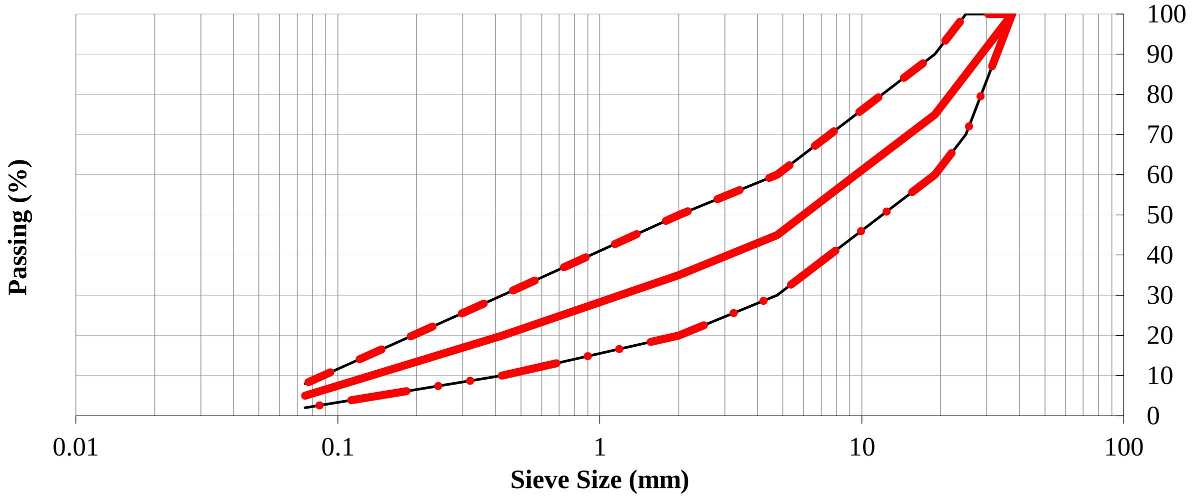


Fig. 2. Aggregation diagram Type 4 (lower, middle, upper limits)

2.2. Compaction and Density Test

In this experiment, which is based on the AASHTO-T265 (Standard AASHTO, 2009), the samples were compacted by 56 hammer blows weighing 4.54 kg from a 457 mm height. After compaction, the mold and compacted wet soil are weighed with an accuracy of 5 g and then, the sample is extracted from the mold and cut vertically from the middle. After which dry density and water content are obtained by Eqs. (1) and (2).

$$W = \frac{W_1}{\omega + 100} \times 100 \tag{1}$$

$$\omega = \frac{A - B}{B - C} \times 100 \tag{2}$$

where ω: is the sample water content, A and B: are the weight of wet and dry soil with mold, respectively, C: is the weight of the mold, and W and W_1: are dry and wet compacted soil (kg/m^3), respectively.

2.3. CBR Test

In this experiment, which is based on the ASTM D 1883-16 (ASTM, 2016), the samples were first compacted by the modified compression method (ASTM D, 2000) and then were loaded. Finally, the CBR rate of each sample was obtained by Eq. (3).

$$CBR = \frac{P_{0.1}}{P} \times 100 \tag{3}$$

where $P_{0.1}$: is the corrective pressure and P: is the standard pressure.

2.4. Optimum Water Content Test

The maximum laboratory specific gravity of a rock mixture depends on the material, water content and compaction test method. This experiment is conducted according to the AASHTO T99-10 Standard (2015), so that first, a sample of the desired stone materials in different water contents is pounded and compacted in the laboratory, then the maximum dry specific gravity is obtained by drawing the compaction curve of the stone materials. The water content in which the dry specific gravity of the stone materials is maximal is called optimum water content.

2.5. Permeability Test

Permeability is the ability of water to flow through saturated soil. The parameter that expresses the permeability rate of soil is called permeability coefficient or hydraulic conductivity coefficient. In this study, the permeability rate was assessed by performing a falling head test. In this test, the water level in a small diameter pipe drops (from the initial value h_0 to the final value h_f) and the time it takes for the water to reach h_f height from h_0 height is measured. The permeability coefficient is calculated using Eq. (4).

$$K = 2.3 \frac{a \times L}{A \times t} log \frac{h_0}{h_f} \tag{4}$$

where K: is the permeability coefficient (cm/s), A: is a pipe inside the cross-sectional area (cm^2), L: is the sample length (cm), h_0 and h_f: are the initial and final height of water in the pipe (cm), respectively, and t: is the recorded time to reach the water height from h_0 to h_f.

2.6. Prime Coat Penetration Test

To prepare the samples, the stone materials were compacted according to aggregate grading Types 3 and 4 of the base layer at 90%, 95% and 100% compaction levels in upper, middle and lower limits and kept in laboratory conditions for 72 hours. After 72 hours of making the samples, the samples are prepared in two modes of dry and wet due to the need to investigate the effect of moisture on the surface of the samples and to compare the bitumen penetration rate in two modes of dry and wet. To make the dry samples, the samples were placed in the open air to dry completely. To make the wet samples, the surface of the samples was saturated with a sprinkler and the additional water was collected by a sponge.

In the existing standards, the amount of bitumen for penetration coating is considered to be between 1600 to 2000 gr/m^2 according to the aggregation conditions. Due to the fact that different types of aggregate grading and compaction levels were investigated in this study and the surface of each sample had different absorption and penetration, the bitumen amount of each sample was calculated and distributed 35 gr according to the diameter of the molds. Finally, after spreading the emulsified bitumen on the surface, the prepared samples were kept in the laboratory for 92 hours to investigate the absorption and penetration of the emulsified bitumen. After the required time, the samples are taken out of the mold by a lifting jack and cut from the middle. Finally, the amount of bitumen penetration into the samples with different aggregate grading and compaction levels were measured.

3. Results and Discussion

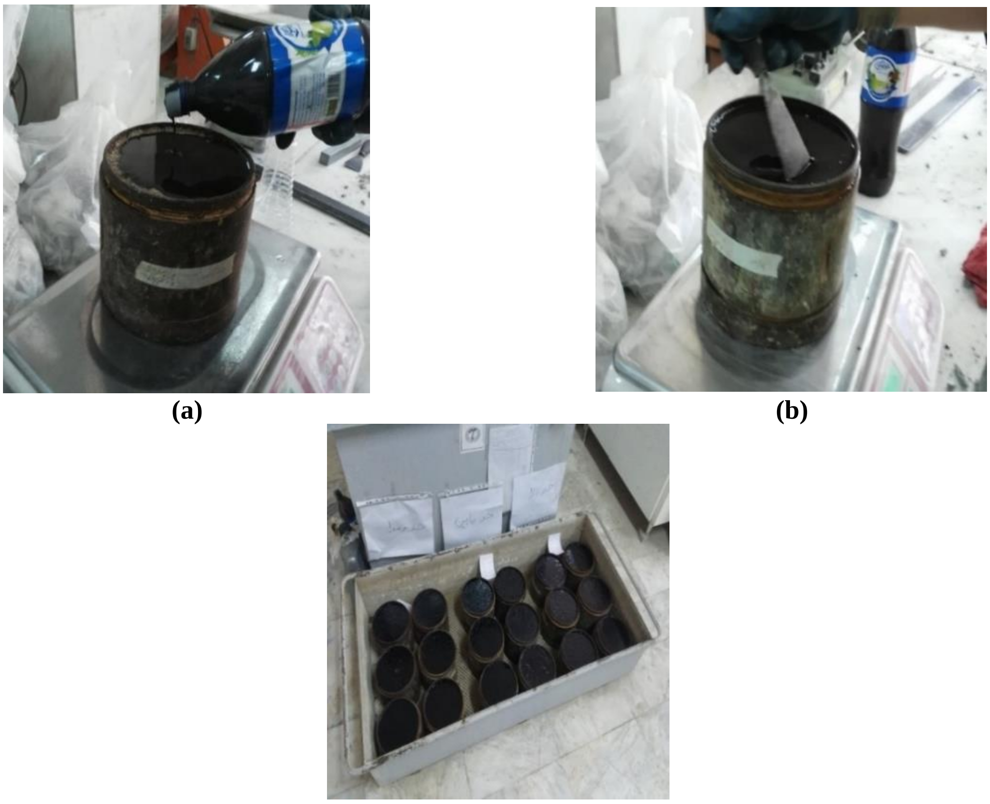
3.1. Density

Dry density values of the base layer with aggregate grading Types 3 and 4 for different types of compaction levels and corresponding to the upper, middle and lower limits can be seen in Figure 2. As shown in Figure 2, the maximum dry density of the samples (γ_{dmax}) decreased with decreasing compaction in all the samples. It is quite natural that the compaction of the samples will decrease due to the lower density. Also, in all samples, the aggregation curve of the upper limit has a higher dry density. Because the upper part of the aggregation curve has finer materials. As a result, the void space in stone materials decreases during the compaction and the dry density of the samples (γ_{dmax}) increases.

3.2. The Effect of Aggregate Grading and Compaction Level on CBR

According to ASTM D1883-16 (ASTM, 2016), the CBR value of the compacted base layer should not be less than 80%. According to Figure 5, all samples with aggregate grading Type 3 had higher values than the specified minimum CBR and had a good compressive strength. It can be concluded that the higher the grain size and compaction, the higher the CBR.

In samples with aggregate grading Type 4, only samples with 100% compaction in all the aggregation limits have the minimum CBR, and in other cases, only the middle and upper limits of 95% compaction and the upper limit of 90% compaction pass the minimum standard. The trend of CBR rate changes in this type of aggregate grading, just as aggregate grading type 3, increases with an increase in compaction and moving of the aggregation towards a smaller size. Comparing the two types of aggregate grading, it can be seen that the samples with aggregate grading Type 3 have a higher compressive strength in all studied cases.



(a) **(b)**

(c)

Fig. 3. Bitumen penetration test: a) Spraying bitumen on the surface to the standard level; b) Bitumen distribution; and c) Placement on the surface of the sample for prime coat penetration

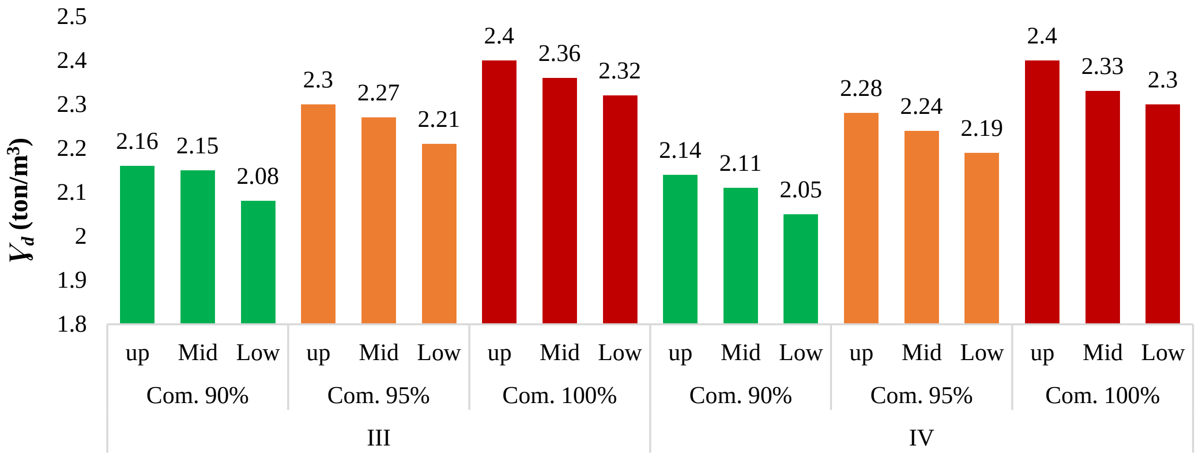


Fig. 4. The density of the base samples in different aggregate grading and compaction levels

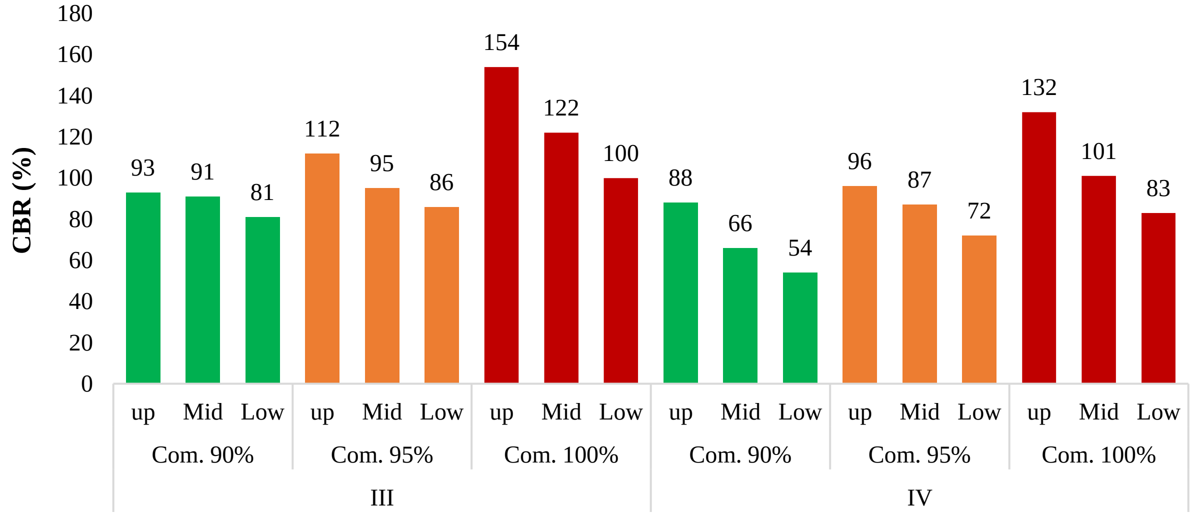


Fig. 5. The CBR of the base samples in different aggregate grading and compaction levels

3.3. The Effect of Aggregate Grading on Optimum Moisture

Comparing the data obtained from the optimum moisture experiment (Figure 6) showed that the closer the aggregate grading is to the upper limit of the aggregation diagrams (the finer the aggregate grading), the higher the optimum moisture percentage. This can also be seen in the aggregate grading change from Type 3 (coarse grain) to Type 4 (finer grain). The reason is that as the aggregate grading becomes smaller, the specific surface of the material increases, and as a result, more moisture is needed in order to moisten the surface of the stone material.

3.4. The Effect of Aggregate Grading and Compaction Level on Permeability

As can be seen in Figure 7, in the samples made according to aggregate grading Type 3, the permeability coefficient is higher in all compaction levels (90, 95 and 100 percent) and the permeability rate has decreased as it approaches the upper limit of the diagram. In other words, the larger the grain size of the sample, the higher the permeability coefficient. As the compaction increases, the amount of cavities between the soil layers and the compaction decreases. According to the penetration rate of the prime coat in samples with aggregate grading Type 4, it can be stated that bitumen penetration coefficient has increased with increasing compaction and reduction of aggregate size (approaching the upper limit) in this type of samples. By comparing the samples with aggregate grading Types 3 and 4, it can be stated that due to the finer nature of Type 3 samples, the penetration coefficient has been lower.

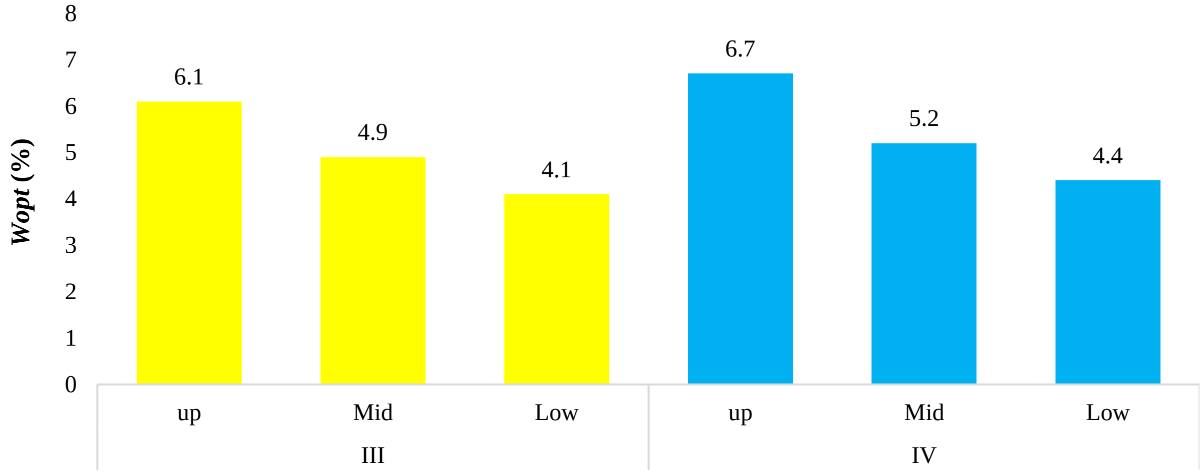


Fig. 6. Optimum moisture of the base samples with different aggregate grading

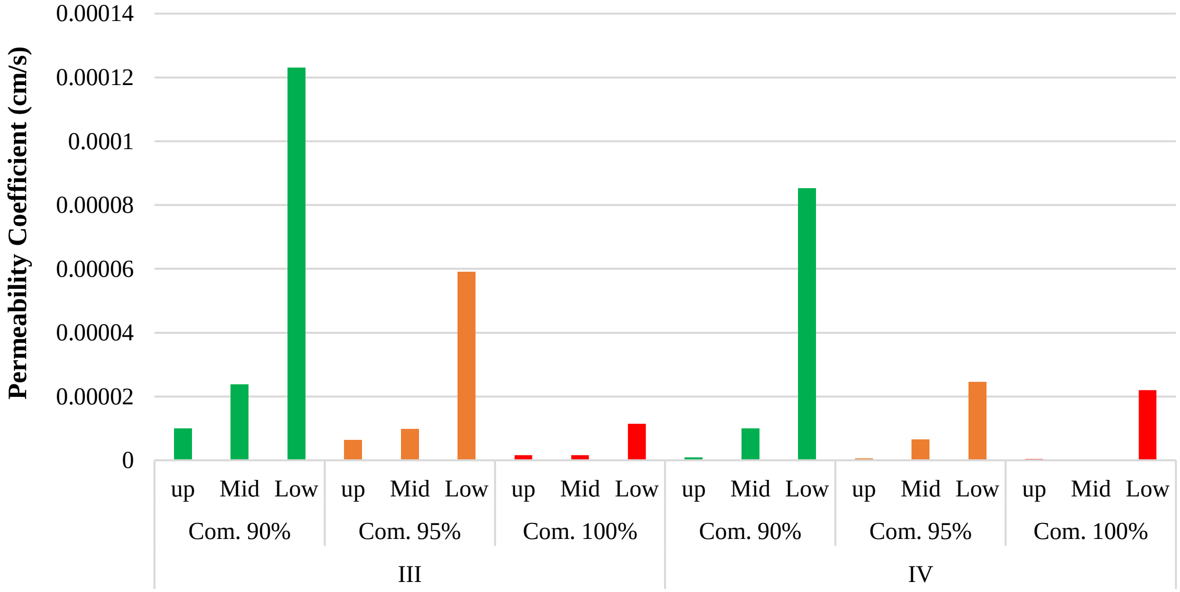


Fig. 7. Permeability of the base samples with different aggregate grading and compaction levels

3.5. Prime Coat Penetration on Dry and Wet Conditions

Figure 8 shows that samples with less compaction have higher bitumen penetration rate. Increasing the grain size in this type of aggregate grading (approaching lower limit) has led to an increase in the penetration rate. Aggregate grading Type 4 is similar to the trend of Type 3, so that the penetration rate has decreased by increasing compaction and decreasing aggregation rate. By comparing the two types of aggregate grading, it can be seen that this bitumen penetration rate in Type 4 was less than Type 3, in all compaction levels and aggregate grading, and this is due to the finer grain size of type 4.

According to Figure 9, it can be stated that the penetration rate of emulsified bitumen into the base layer has decreased by increasing the compaction and also the penetration rate has decreased by approaching the upper limit and decreasing the aggregate size. A similar trend is seen in aggregate grading Type 4 in terms of penetration due to the compaction rate and type of aggregation. Aggregate grading Type 3 has more permeability for emulsified bitumen in wet condition. By comparing wet and dry conditions in both aggregate grading (Figures 8 and 9), it can be stated that the moisture of the base layer improves the penetration rate of emulsified bitumen in all compaction levels and aggregate grading.

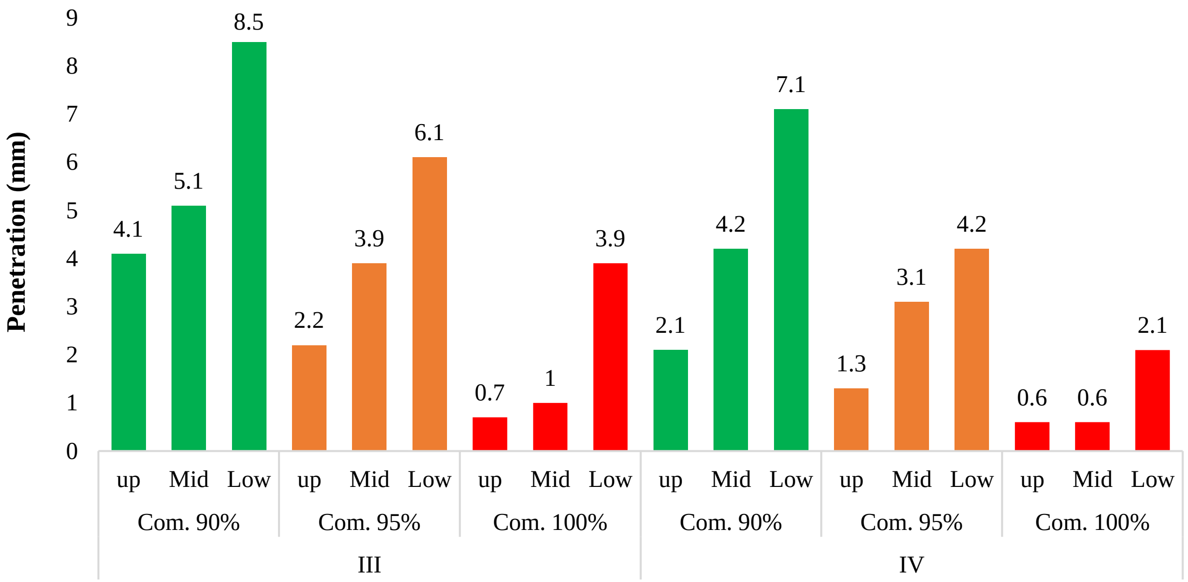


Fig. 8. Prime coat penetration rate in the base samples with different aggregate grading and compaction levels on dry condition

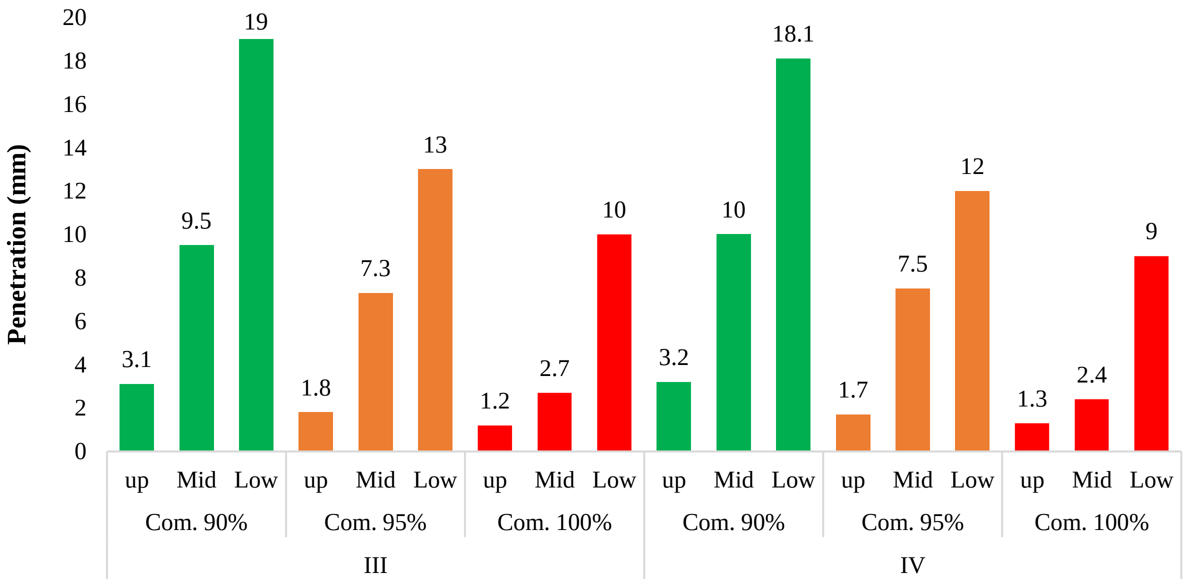


Fig. 9. Prime coat penetration rate in the base samples with different aggregate grading and compaction levels on dry condition

4. Conclusions

In this study, first the characteristics such as density, optimum CBR moisture and permeability of the samples with different compaction levels and aggregate grading were measured, and then the penetration rate of emulsified bitumen CSS-1h was investigated as a prime coat coating in samples with different compaction levels and aggregate grading, in order to evaluate the penetration rate of prime coat coatings in the grain base layer. The results of the experiments are as follows:

- With decrease in aggregation, the density and optimum water content of the samples increase. Also, increase in the compaction level increases the density of the samples.
- Samples with aggregate grading Type 3 have sufficient compressive strength in all aggregate boundaries and this resistance increases with decreasing the aggregation size (approaching upper limit) and increasing the compaction level, but in samples with aggregate grading Type 4, only samples with a 100% compaction have the required

compressive strength in all aggregate boundaries and only finer-grained samples retain their compressive strength by reducing the compaction level.

- Decreasing the grain size has reduced the permeability of the samples, but as the compaction increases, the permeability of the samples decreases.
- Coarse-grained samples (aggregate grading Type 3 or aggregation near the upper limit) and lower compactions have higher bitumen penetration on dry condition, which means that the prime coat penetration increases if the moisture increases in these samples.

5. References

AASHTO T99-10 Standard. (2015). *99: Moisture-density relations of soils using a 2.5-kg (5.5-lb) rammer and a 305-mm (12-1 in.) drop*, Standard Specifications for Transportation Materials and Methods of Sampling and Testing 2.

AASHTO (2013). *Sizes of aggregate for road and bridge construction (M 43-05)*, AASHTO, Washington, DC.

ASTM, D. (2000). *1557: Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))*, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, United States.

ASTM, D1883-16 (2016). *Standard test method for California bearing ratio (CBR) of laboratory-compacted soils*, West Conshohocken, PA, United States.

Bastidas-Martínez, J.G., Ruge, J.C., Paba, I.J., Vasquez, F. and Rojas Suárez, J.P. (2020). “Physical mechanical performance of asphaltic emulsions in road oil for flexible pavements“, *Journal of Physics: Conference Series*, 1645, 012011.

Behbahani, H., Hamedi, G.H. and Najafi Moghaddam Gilani, V. (2020). “Predictive model of modified asphalt mixtures with nano hydrated lime to increase resistance to moisture and fatigue damages by the use of deicing agents“, *Construction and Building Materials*, 265, 120353.

Chhorn, C. and Lee, S.W. (2018). "Influencing compressive strength of roller-compacted concrete", *Proceedings of the Institution of Civil Engineers - Construction Materials*, 171(1), 3-10.

Chun, S., Kim, K., Park, B. and Greene, J. (2017). "Evaluation of structural benefits of prime coat application for flexible pavements using accelerated pavement testing (APT)", *KSCE Journal of Civil Engineering*, 21(1), 141-149.

Cross, S.A., Voth, M.D. and Shrestha, P.P. (2005). “Guidelines for prime coat usage on low-volume roads“, *Transportation Research Record*, 1913(1), 117-125.

Freeman, T.J., Button, J.W. and Estakhri, C.K. (2010). "Effective prime coats for compacted pavement bases", No. FHWA/TX-10/0-5635-1. 2010.

Hu, X., Lei, Y., Wang, H., Jiang, P., Yang, X. and You, Z. (2017). "Effect of tack coat dosage and temperature on the interface shear properties of asphalt layers bonded with emulsified asphalt binders", *Construction and Building Materials*, 141, 86-93.

Huang, Y.H. (2004). *Pavement analysis and design*, Second Edition, Pearson Publication.

Ishai, I. and Livneh, M. (1984). “Functional and structural role of prime coat in asphalt pavement structures“, In: *Association of Asphalt Paving Technologists Proceedings*, Vol. 53, 98-118.

Kucharek, A.S., Eng, P., Scarborough, O., Davidson, J.K. and Kennedy, M. (2008). "Development of a solvent-free asphalt emulsion for prime coats and granular sealing", In: *Proceedings of the Fifty-third Annual Conference of the Canadian Technical Asphalt Association (CTAA) Canadian Technical Asphalt Association (CTAA)*, 84-102.

Mantilla, C.A., and Button, J.W. (1994). *Prime coat methods and materials to replace cutback asphalt*, Technical Report, Report No. FHWAffX-94/1334-lF, U.S. Department of Transportation, Virginia.

Mohan, G., Yildirim, Y., StokoeII, K.H. and Erten, M.B. (2013). "Engineering properties of prime coats applied to a granular base", *Journal of Testing and Evaluation*, 41(5), 713-718.

Motamedi, H., Amiri, H.R., Fazaeli, H. and Mohammad Aliha, M.R. (2021). "Providing a prediction model for stress intensity factor of fiber-reinforced asphalt mixtures under pure mode III loading using the Edge Notched Disc Beam (ENDB)", *Civil Engineering Infrastructures Journal*, 54(1), 43-58.

Ouyang, J., Sun, Y. and Zarei, S. (2020). "Fabrication of solvent-free asphalt emulsion prime with high penetrative ability", *Construction and Building Materials*, 230, 117020.

Šernas, O., Zofka, A., Vaitkus, A. and Gražulytė, J. (2020). "The effect of exposed aggregate concrete gradation on the texture characteristics and durability", *Construction and Building Materials*, 261, 119921.

Slaughter, G. (2004). "Environmental comparison of cutback bitumen and bitumen emulsions for sealing roads", *Towards Sustainable Land*

Transport Conference, Wellington, New Zealand.

Standard, A.A.S.H.T.O. (2009). *T265: Standard method of test for laboratory determination of moisture content of soils*, Standard Specifications for Transportation Materials and Methods of Sampling and Testing. American Association of State Highway Officials, Washington.

Taherkhani, H. (2016). "Investigating the effects of nanoclay and nylon fibers on the mechanical properties of asphalt concrete", *Civil Engineering Infrastructures Journal*, 49(2), 235-249.

Taherkhani, H. and Afroozi, S. (2017). "Investigating the performance characteristics of asphaltic concrete containing nano-silica", *Civil Engineering Infrastructures Journal*, 50(1), 75-93.

Transportation Officials. (1993). *AASHTO Guide for design of pavement structures*, Vol. 1, Aashto. Washington.

Vignarajah, M., Leaverton, M. and Senadheera, S. (2007). *Constructability review of surface treatments constructed on base courses*, Technical Report, Report No. 0-5169-2, U.S. Department of Transportation, Virginia.

Wang, G., yi Wang, D. and ning Li, D. (2017). "Laboratory study and performance evaluation of a new type of prime coat material used on cement treated base", *Construction and Building Materials*, 147, 588-597.

Xu, G., Shen, W., Huo, X., Yang, Z., Wang, J., Zhang, W. and Ji, X. (2018). "Investigation on the properties of porous concrete as road base material", *Construction and Building Materials*, 158, 141-148.

Zhang, Q., Xu, Y.-h. and Wen, Z.-g. (2017). "Influence of water-borne epoxy resin content on performance of waterborne epoxy resin compound SBR modified emulsified asphalt for tack coat", *Construction and Building Materials*, 153, 774-782.