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Variation of Quality of Roller-Compacted Concrete Based on Consistency

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***Abstract*—**Roller-compacted concrete (RCC) has been used for decades in many pavement applications due to its economic cost and high construction speed. However, due to the lack of deep researches and experiences, this material has not been widely employed. An RCC mixture with appropriate consistency can induce high compacted density, while high density can induce good aggregate interlock and high strength. Consistency of RCC is mainly known to define its constructability. However, it was not well specified how this property may affect other properties of a constructed RCC pavement (RCCP). This study suggested the possibility of an ideal range of consistency that may provide adequate quality of RCCP. In this research, five sections of RCCP consisted of both 13 mm and 19 mm aggregate sections were investigated. The effects of consistency on compacted depth, strength, international roughness index (IRI), skid resistance are examined. From this study, a new range of consistency is suggested for RCCP application.

***Keywords*—**Compacted depth, consistency, international roughness index, pavement, roller-compacted concrete, skid resistance, strength.

I. Introduction

RCC is an economical, fast-construction candidate for many pavement applications. It has traditionally been used for pavements carrying heavy loads in low-speed areas. For instance, RCCP was used in intermodal yard paving projects at the Port of Tacoma, Washington due to a substantial cost savings over conventional Portland cement concrete and asphaltic concrete pavement when used in heavy wheel load applications [1]. The first heavy-duty RCCP in the US was constructed in the railroad intermodal hub faculty for Burlington Northern at Houston, Texas [2]. In pavement application, this concrete needs no forms or finishing, and there are no dowels, tie rods, or steel reinforcement. Besides the reduced construction costs, its principal advantage for mass construction is the low cement content of the mixture which greatly reduces problems due to the heat of hydration of cement [3]. Even though concrete strength highly depends on hydration, the compaction can significantly enhance density of RCC as well as its load carry capacity or strength. Well compacted and high density RCC is crucial for improving its aggregate interlock and removing the excessive air. With these mechanical and chemical processes, a dense pavement that has properties similar to those of conventional concrete pavement can be attained. This concrete, however, is not widely used due to the lack of in depth researches and experiences.

It should be pointed out that it is often much easier to achieve high strength RCC in the controlled conditions of the laboratory than in the field where several unexpected factors can affect production and placement operations. Proper mixture design and good quality control at batch plant can significantly affect the fresh properties and quality of the final product of RCCP. Consistency is one of the main properties for quality control of RCC during construction and this property can be influenced by many factors such as: aggregate gradation, water content, cement content, admixtures, etc. Consistency is the key parameter for defining the constructability of RCC. Due to its stiffness, typical slump test cannot be applied on this concrete. Vebe test [4] is generally used to measure the consistency of an RCC mixture, and Vebe time is its measurement. To perform the test, the specimen is placed on a vibrating table. From this test, the consistency or Vebe time of concrete is determined by the vibrating time of the table to the point when mortar ring is observed in the specimen. There are two methods in this test, method A and B, which is based on the stiffness of concrete. In method A, a surcharge of 22.7 kg is applied on top of the material filled inside the specimen during the vibration. Method B, in which no surcharge is used, is applied when Vebe time in method A is found less than 5 seconds. The second method, however, is not applicable for RCCP. Big aggregate can sometimes prevent the mortar ring from forming. Thus, many replications may be required for the test. It is important to achieve an RCC mixture with appropriate consistency. If the mixture is not stiff enough or too wet, the material would go disintegrate during placement or compaction. If the mixture is too stiff or too dry, maximum density may not be acquired and thus extra compacting energy may be required. In order to acquire high compacted density, appropriate consistency of RCC mixture should be attained. With high density, good aggregate interlock and high strength can be secured. According to [5], appropriate range of Vebe time for RCC in pavement application is from 30 to 40 seconds. On the other hand, it was suggested by [6] that Vebe time ranged from 50 to 75 seconds is also applicable on RCC in pavement application. However, it is unclear which Vebe time range is more beneficial. As a result, the use of Vebe time ranged between 30 and 75 seconds should be investigated in RCCP construction. In this research, the effect of consistency on mechanical and surface properties of RCCP shall be discussed.

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II. Strategy to Investigate Consistency of RCC

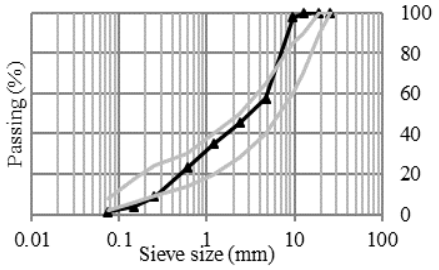
A. Test Sections

Five sections of RCCP were constructed in Seokcho of South Korea. Overall length of the pavement was 580 m with 5 m width and 20 cm thickness. The purpose of this construction was to test the construction equipment and to check the constructability and performance of RCCP with different maximum aggregate size (13 mm and 19 mm) under real environment condition. The mixture proportioning of each section is given in Table I. The optimum mixture in each case was selected based on Soil Compaction Method [7] and Vibrating Table Test [4]. The criterion for the optimum mixture is to achieve a mixture with maximum density and appropriate consistency (Vebe time between 30 to 75 seconds).

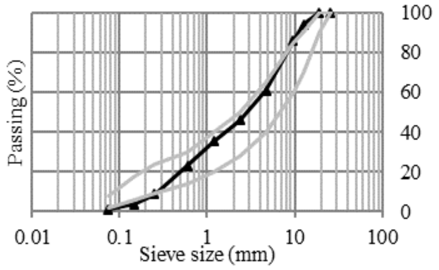
TABLE I
Mixture Design of Each Section for One Cubic Meter

Section	Max. agg. (mm)	AEA (kg)	PNS (kg)	W (kg)	C (kg)	S (kg)	G (kg)
1	19	0.28	0	107	280	1032	1072
2	13	0.28	0	107	280	1032	1071
3	13	0.28	0.14	104	280	1036	1075
4	19	0.28	0.14	107	280	1032	1072
5	19	0.28	0	107	280	1032	1072

Max. agg= Maximum aggregate, AEA = Air Entraining Agent, PNS = Poly Naphthalene Sulfonate superplasticizer; W = Water, C = Cement, S = Sand, G = Gravel.



(a)



(b)

Fig. 1 Aggregate gradation for (a) 13 mm aggregate sections, (b) 19 mm aggregate sections (actual gradation, black; recommended upper and lower limit by PCA, grey)

B. Materials

In this study, crushed aggregates with maximum aggregate size of 13 mm and 19 mm are used. Fine aggregate and coarse aggregates (19 mm and 13 mm) were proportioned at 50% of sand/aggregate ratio with gradations as shown in Fig. 1. Ordinary Portland cement was employed. Air entrained agent and polynaphthalene sulfonate superplasticizer were also used in order to provide adequate durability and workability of this concrete.

C. Construction and Data Collection

The 580 m RCCP was constructed within one day and the construction process consisted of material mixing and transportation, paving, compacting and curing which are shown in Fig. 2. At batch plant, Vebe test was conducted twice for each section (except section 4). This test, however, was learnt to be impractical due to its time consumption and testing location. Dump truck with 12 m^3 of carrying capacity was used to transport RCC from batch plant to construction site. Various sensors were also installed during the construction for measuring temperature, earth pressures, and stress-strain for other study purposes.

(a) (b)

(c) (d)

Fig. 2 Construction process of RCCP (a) Mixing and transportation, (b) Paving, (c) Compaction, (d) Curing

III. Effect of Consistency on Quality of RCCP

According to other researches, various ranges of Vebe time for RCC in pavement application were recommended between 30 and 75 seconds. Although this range seemed to be narrow, high variability was still observed in other properties of RCCP with variation of Vebe time. It is known that high Vebe time indicates a stiff and dry mixture, while low Vebe time indicates a less stiff and wet mixture. This property plays an important role in determining the constructability of an RCCP. Its impact on the performance of this pavement, however, is still questionable. In this study, the effect of consistency or Vebe time on mechanical and surface properties of RCCP shall be discussed. By correlating Vebe time to each property of RCCP, it may be possible to define an ideal consistency or Vebe time for a good quality RCCP.

A. Compacted Depth

Although high strength and density are desired in RCCP, it is also important to have RCC compacted throughout the whole depth. Without full compaction, a strong structure and adequate load carry capacity may not be achieved. In this study, compacted depth ratio is used to represent how well RCC is compacted in each section. It should be pointed out that compacted depth ratio is the ratio between well compacted depth and total coring depth of a specimen from the pavement section as shown in Fig. 3. The relationship between Vebe time and compacted depth ratio was given in Fig. 4. The two parameters seemed to be correlated in parabolic form, and the optimum Vebe time was found at 55 seconds for the maximum compacted depth ratio. This indicated that an optimum value of Vebe time or consistency should be acquired in order to maximize compacted depth of this concrete. However, it is unrealistic to set a fix value for consistency of RCC considering its high water sensitivity and moisture variation in aggregates at batch plant. From Fig. 4, it is recommended to use Vebe time ranged between 47 to 65 seconds to maintain the compacted depth at least 95 percent of its whole depth.

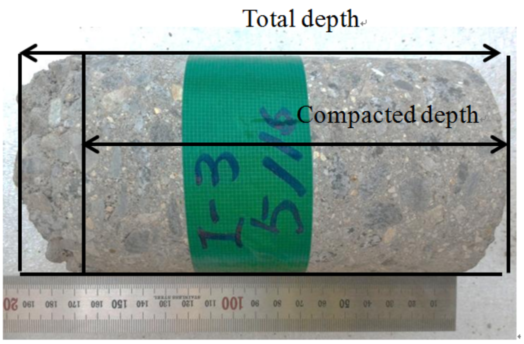


Fig. 3 Measurement of compacted depth

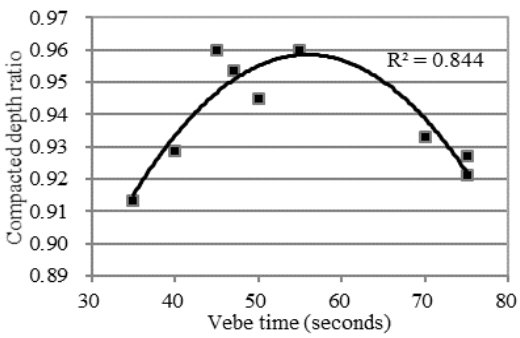
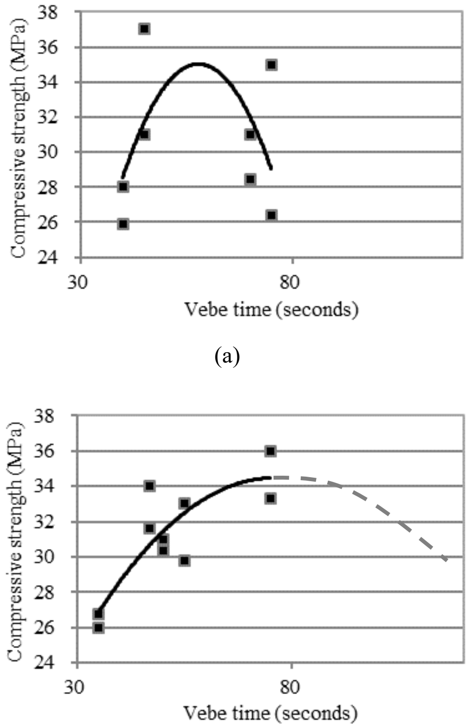


Fig. 4 Relationship between Vebe time and compacted depth ratio

B. Compressive Strength

Vebe time or consistency is highly correlated with water content. Thus, Vebe time can be used to represent water content. However, it should be noted that high Vebe time implies dry or low water content mixture, while low Vebe time implies wet or high water content. The relationship between compressive strength and water content should be in parabolic form and so thus for the relationship between compressive strength and Vebe time. The relationship between Vebe time and compressive strength at 28 days of RCC for 13 mm and 19 mm aggregates was given in Fig. 5. Due to the lack of data point, clear parabolic curve cannot be drawn for both cases. The optimal compressive strength for 13 mm section is likely to fall within the recommended range, while the optimal strength for 19 mm section tends to lean toward higher Vebe time or stiffer condition. Interestingly, compressive strength within Vebe time of 47 to 65 seconds (recommended range) in both cases was found higher than 30 MPa, which could satisfy the concrete pavement criteria in Korea. In average, the compressive strength of 19 mm aggregate sections gave 11% higher than that of 13 mm aggregate sections. Thus, the reduction in strength due to the change of maximum aggregate size was observed. The requirement for hydration should also be considered during the selection of optimal water content.



(b)

Fig. 5 Relationship between Vebe time and compressive strength at 28 days for (a) 13 mm sections, (b) 19 mm sections

C. International Roughness Index (IRI)

Many factors such as construction equipment and construction method may also affect the roughness property. However, only effect of consistency on IRI is focused in this study. It is known that low IRI represents a good surface smoothness, while high IRI represents the other way around. The relationship between Vebe time and IRI of RCCP for 13 mm and 19 mm aggregate sections were given in Fig. 6. Although their data points seemed to be scattering, the trend line of the combination of 13 mm and 19 mm aggregate sections can indicate its optimal point at 55 seconds of Vebe time. The same trend was previously found in compacted depth ratio. These results indicated that good compaction of RCC can also enhance its compacted surface smoothness. The average IRI of 19 mm aggregate sections and that of 13 mm aggregate sections were found to be insignificantly different. Their surface smoothness was not good enough for highway application according to IRI roughness scale replotted by [8]. Thus, surface enhancement such as diamond grinding or AC overlay may be required.

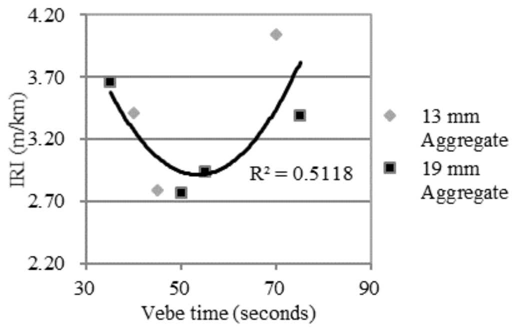


Fig. 6 Relationship between Vebe time and IRI for 13 mm and 19 mm aggregate sections

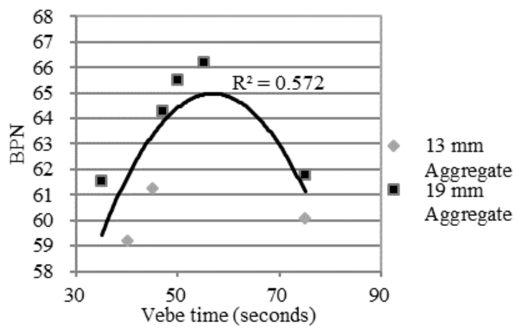


Fig. 7 Relationship between Vebe time and BPN for 13 mm and 19 mm aggregate sections

D.Skid Resistance

An appropriate skid resistance is required in order to guarantee a safe pavement surface. It is known that high BPN gives high skid resistance, while low BPN gives low skid resistance. In this study, the relationship between Vebe time and BPN of RCCP for 13 mm and 19 mm aggregate sections was investigated (Fig. 7). From the graph, it was found that Vebe time and BPN are correlated in parabolic form. This indicated that skid resistance of RCCP tends to increase when RCC mixture gets stiffer. For dry mixture, the amount of mortar may not be enough to cover the surface area which allows the expose of aggregate texture after compaction and thus resulting high skid resistance. For wet mixture, on the other hand, sufficient amount of mortar can cover and fill the void between aggregates at the surface area which may cause slippery and low friction surface. However, as the mixture gets too stiff, skid resistance starts to decrease. Although this phenomenon cannot be physically explained, similar trend was previously found in relationship between Vebe time and IRI. Further study and more data are required in order to confirm this phenomenon. In this study, the optimal Vebe time for BPN was found at 55 seconds. Overall, skid number in both cases was relatively high, and the average value of BPN in 13 mm aggregate sections was found slightly lower than that in 19 mm aggregate sections.

IV. Conclusion

Appropriate consistency is not only necessary for adequate workability but also high performance RCCP. This property was found to be highly correlated to performance of RCCP. In RCC mixture, Vebe time of 55 seconds should be acquired in order to maximize compacted depth, skid resistance and minimize IRI. However, it is not realistic to set a fix value for consistency of RCC considering its high water sensitivity. It is recommended to use Vebe time range from 47 to 65 seconds for RCCP application. RCC mixture with Vebe time within this range tends to provide relatively high compacted depth, strength, skid resistance, and low IRI. However, it may vary depending on construction equipment and process.

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