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DEVELOPMENT OF NORTH AMERICAN GUIDELINES FOR PREQUALIFICATION OF BEDDING SAND FOR USE IN SEGMENTAL CONCRETE PAVEMENTS IN VEHICULAR APPLICATIONS

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Note: The following is the notation used in this paper: (.) for decimals and (   ) for thousands.

Summary

Bedding sands are a critical component of all sand-set segmental concrete paving systems. Failure of the bedding sand layer has occurred in channelized vehicular loads from two main actions; structural failure through degradation and saturation due to inadequate drainage. Typical North American specifications require bedding sands to conform to ASTM C 33 and CSA A 23.1 (FA1) gradation for concrete sands with additional limits on the allowable amount of material that passes the 0.075 mm sieve. While gradation is an important consideration for bedding sand selection, other characteristics should be assessed for vehicular applications in order to ensure long-term pavement performance.

This paper reviews relevant international research, presents the characteristics of good performing North American bedding sands from a study conducted by the Interlocking Concrete Pavement Institute [ICPI, 2004], and presents recommendations for prequalification of bedding sands for vehicular traffic. Primary material property limits are introduced for prequalifying bedding sands including degradation using the Micro-Deval test procedure and drainage using the constant head permeability test method. Secondary material properties are also suggested for prequalification, including sodium sulfate or magnesium sulfate soundness, silica/carbonate ratio, and particle shape/angularity. This paper provides guidance on bedding sand selection to specifiers and contractors for vehicular applications.

1. INTRODUCTION

All sand-set segmental concrete paving systems in street or heavy-duty industrial, port or airport pavements require special attention to bedding sand selection. While the North American specifying community industry has relied mostly on gradation requirements for prequalification of bedding material, experience and international research has demonstrated that other characteristics should be assessed in order to ensure long-term pavement performance of vehicular pavements. This paper reviews important characteristics identified through previous research, material property research on bedding sands [ICPI, 2004] conducted by the Interlocking Concrete Pavement Institute (ICPI) using North American standard test methods, and provides guidance to specifiers and contractors for selection. For the purposes of this paper, and the recommendations herein, vehicular traffic is defined as a minimum of 1.5 million lifetime 80 kN equivalent single axle load (ESALs) with axle loads up to 11 000 kg or with a maximum vehicle load of 22 680 kg.

2. CURRENT GUIDELINES

Bedding sand provides four main functions that include:

- Bedding the pavers during installation,
- Initializing interlock among the pavers,
- Providing a structural component for the system, and
- Facilitating water drainage that infiltrates through the paver joint sand.

North American guide specifications for interlocking concrete pavements require bedding sands to conform to gradations according ASTM C33 or CSA A23.1 (FA1) for all project types (see Tables 1 and 2). The sands are typically called "concrete sands" referring to those sands used to manufacture ready-mix concrete. The ICPI provides additional limits on material passing the 0.075 mm sieve beyond those required by these standards.

The importance of gradation is also emphasized in other countries. [Knapton, 1994] noted that since 1980 the amount of material passing the 0.075 mm sieve has been reduced in the British Standard BS 7533-1 Guide for the Structural Design of Heavy Duty Pavements Constructed of Clay or Concrete Pavers [British Standard, 2001]. Knapton noted that the allowable material passing the 0.075 mm sieve has been reduced from 10% in 1980, to 3% in 1991 and to 1% for heavily trafficked pavements. For bus stations, the reduction is 0.1% passing.

Table 1. ASTM C 33 requirements.

SIEVE SIZE	PERCENT PASSING
3/8 in. (9.5 mm)	100
No. 4 (4.75 mm)	95 to 100
No. 8 (2.36 mm)	85 to 100
No. 16 (1.18 mm)	50 to 85
No. 30 (0.600 mm)	25 to 60
No. 50 (0.300 mm)	10 to 30
No. 100 (0.150 mm)	2 to 10
No. 200 (0.075 mm)	0 to 1*
* refers to recommended limit from ICPI.	

Table 2. CSA A23.1 (FA1) requirements.

SIEVE SIZE	PERCENT PASSING
10 mm	100
5 mm	95 to 100
2.5 mm	80 to 100
1.25 mm	50 to 90
0.630 mm	25 to 65
0.315 mm	10 to 35
0.160 mm	2 to 10
0.075 mm	0 to 1*
* refers to recommended limit from ICPI.	

3. FAILURE MECHANISMS

Bedding sand layer failure can occur in channelized vehicular loads from two main actions; structural failure through degradation and saturation due to inadequate drainage. Since bedding sands are located high in the pavement structure, they are subjected to repeated applications of high stress from vehicles passing over the pavement [Beaty, 1996]. This repeated action, particularly from high bus and truck axle loads, degrades the bedding sand, and causes failure. For these applications, sand should be selected based on their ability to withstand long-term degradation.

In regularly trafficked vehicular applications, other factors besides gradation contribute to the successful function of the bedding layer. Other studies [Lilley and Dowson, 1988] [Beaty, 1996], investigated failures of interlocking concrete pavements subjected to channelized vehicular traffic. They concluded that more comprehensive specifications are required that address other properties in addition to gradation. [Lilley and Dowson, 1988] suggested that bedding sands that carry more than 1.5 million equivalent 80 kN axle loads should be subjected to grading and degradation tests.

Bedding sand permeability also is a significant factor in the selection process. Whenever difficulties have been experienced with laying course materials in heavily trafficked pavements, water in that layer has been a major factor [Knapton, 1994]. As bedding sands approach higher moisture levels in service, they may become unstable. Smaller particle sizes (fines) become suspended in water, forming slurry that lubricates the entire bedding layer. Choosing bedding sand with gradations shown in Tables 1 and 2 will help reduce the risk of poor drainage and instability. However, these sands will be susceptible to drainage problems if they do not have the hardness to withstand long-term degradation from vehicular wheel loads.

4. GOING BEYOND GRADATION

4.1 Durability Testing

Aggregate durability has long been understood as a major factor in any pavements performance. ASTM C88 *Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate* [ASTM, 2005] is a typical test method used by road agencies to assess aggregate durability for road base. The test involves soaking an aggregate in a solution of magnesium or sodium sulfates and oven drying. This is repeated for a number of cycles, with each cycle causing salt crystals to grow and degrade the aggregate. The test takes at least six days. The percent loss is then calculated on individual particle size.

This test method, however, is considered highly variable. When ASTM initially adopted this test method the lack of precision was recognized as follows, "it may not be suitable for outright rejection of aggregates without confirmation from other tests more closely related to the specific service intended." [Jayawickrama, 2006]

The Micro-Deval test has evolved as the test method for evaluating durability of aggregates in North America. It is defined by CSA A23.2-23A, *The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* [CSA, 2000], and ASTM D 7428 *Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* [ASTM, 2008]. The test method involves subjecting aggregates to abrasive action from steel balls in a laboratory rolling jar mill (see Figure 1). A 500 g representative sample is obtained after washing to remove the 0.080 mm material. The sample is saturated for 24 hours, and placed in a stainless steel jar, with 1250 g of steel balls and 750 ml of tap water.

Figure 1. The Micro-Deval test apparatus (Source: Geneq, Inc.).

The jar is turned at 100 rotations per minute for 15 minutes. After rotation, the sand is separated from the steel balls over a sieve and the sample of sand is washed over a .075 mm sieve. The material retained on the sieve is oven dried. The Micro-Deval loss is calculated as the total loss of original sample mass expressed as a percentage.

A study conducted by the Interlocking Concrete Pavement Institute [ICPI, 2004] investigated nine sands from across the United States reported by contractors rated with "poor to excellent" long term serviceability in vehicular applications. The results of the study (see Table 3) indicated that eight of the sands had Micro-Deval degradation losses less than 8% when measured according to CSA A23.2-23A [CSA, 2000] and these were associated by those contractors as having "good to excellent" field performance.

The same study subjected these sands to the ASTM C 88 soundness loss and found that none of the samples associated with "very good to excellent" ratings had greater than 6% soundness loss. As previously noted, the variability of the soundness test results should always be a consideration unless measured in relation to other material properties. ICPI recommends that the Micro-Deval test be used as the primary means to characterize bedding sand durability (see Table 4) and the magnesium or sodium sulfate soundness tests should be considered when the Micro-Deval test is not locally available.

Table 4 summarizes the primary and secondary material properties resulting from the ICPI study that are recommended in North America when selecting bedding sands for vehicular applications. Bedding sands may exceed the gradation requirement for the maximum amount passing the 0.075 mm sieve as long as the sand meets degradation and permeability recommendations in Table 4. Micro-Deval degradation testing can be replaced with sodium or magnesium sulfate soundness testing as long as this test is accompanied by the other primary material property tests listed in Table 4. Other material properties listed, such as petrography and angularity testing are at the discretion of the specifier and may offer additional insight into bedding sand performance. These properties are discussed later in this paper.

4.2 Assessing Drainage

Drainage of the bedding layer is important for early and long-term pavement performance. One failure documented describes a segmental pavement in a northwestern U.S. city that opened to bus traffic and within hours of construction subjected to continuous heavy rain [Knapton, 1993]. The bedding sand had a high percentage of fines. The rainfall transported the finer sieve sizes into the drain holes of the underlying concrete slab. With compromised drainage the bedding sand liquefied and pumped through the joints of the pavement from repeated bus traffic, resulting in immediate rutting and failure.

The pavement was subsequently reconstructed with harder bedding sand with 0% material passing the 0.075 mm sieve and the results yielded excellent performance. It was clear from this failure and the reconstruction that hardness and gradation were important factors and both were related to permeability. Even specifications that allow up to 3% of fines can result in a five-fold decrease in permeability from the lowest (0%) to highest (3%) percentage passing [Bullen, 1998].

Further research was also conducted on the permeability of the sands rated by contractors as "very good to excellent." [ICPI, 2004]. Using ASTM D2434-68 *Standard Test Method for Permeability of Granular Soils (Constant Head)* [ASTM, 2006], permeability of these sands ranged from 2.1 x 10^{-3} cm/second to 1.1 x 10^{-2} cm/second (see Table 3). These values correspond to fines passing the 0.075 mm sieve that range from 0 to 2.5% passing the 0.075 mm sieve. These same sands were also associated with Micro-Deval maximum degradation values of 8%. Table 4 indicates a minimum permeability of 2.1 x 10^{-3} cm/second as a primary property that should also be considered for vehicular applications.

4.3 Particle Shape

Other studies have also shown that bedding sand particle shape plays a role in performance. [Knapton, 1993] noted that rounded or cubical grains lead to stable sands, whereas more angular grains are frequently associated with sands that fail. The same sands tested by ICPI showed that eight of the nine "good to excellent" performing sands had a predominance of sub-angular to sub-rounded particle shapes when tested according to ASTM D 2488 *Description and Identification of Soils (Visual-Manual Procedure)* [ASTM, 2000](see Table 3).

Specifiers and contractors should consider bedding sand angularity using Figure 2 as a guide. Figure 3 shows a photograph of one of these sands at high magnification. Table 4 suggests as a secondary property, that a combined percentage of sub-angular to sub-rounded particles should be a minimum of 60%.

Table 3. Material Test Results from ICPI Bedding Sand Research.

FPR	**E**	**VG**	**VG**	**VG**	**VG**	**VG**	**VG**	**VG**	**G**	**P**
Sample Number	406-2	406-4	406-5	406-6	1231	1232	1255	1323	406-3	406-1
TEST										
Soundness loss (%)	3.6	3.8	3.2	5.1	2.9	5.7	5.1	2.0	9.0	7.1
Permeability (cm/s x 10^{-3})	3.87	5.59	10.61	2.07	5.69	3.95	4.01	4.97	1.05	1.94
Micro Deval Abrasion Loss (%)	6.1	7.3	4.1	6.9	3.8	7.5	6.3	4.9	15.5	20.4
Wash passing 0.075 mm sieve (%)	0.2	1.7	0.5	2.5	0.0	---	0.9	1.1	1.9	1.0
Shale content (%)	1.2	1.4	0.5	0.0	0.4	0.0	0.0	0.0	8.1	7.4
Chert content (%)	0.0	0.0	0.0	0.0	1.3	0.0	7.2	0.0	3.3	2.9
Silica/Carbonate ratio	Pred. silica	Pred. silica	Pred. silica	Pred. silica	Pred. silica	Pred. silica	80/20	Pred. silica	50/50	50/50
FPR = Field performance rating by contractors (E = excellent, VG = very good, G = good, P = poor) Pred. = Predominant										

4.4 Petrographic Analysis

Several studies have noted petrography or mineral content playing an important role in bedding sand performance. Quartz mineralogy is preferred over crushed sandstones [Knapton, 1993]. In the ICPI study, eight of the nine "good to excellent" performing sands consisted predominately of silica minerals with over 80% of the material either quartz or quartzite (See Table 3). Table 4 recommends a minimum 80/20 ratio of silica/carbonate mineralogy as a secondary property.

A tenth sample, included in the study (and noted as poor performing in the field) was characterized as having up to 50% carbonate content. Petrographic analysis was conducted according to the Ministry of Transportation of Ontario laboratory method MTO LS-616 *Procedure for the Petrographic Analysis of Fine Aggregate* [MTO, 2006]. ASTM C 295 *Standard Guide for Petrographic Examination of Aggregates for Concrete* [ASTM, 2003] offers an alternative test method.

Table 4. Primary and Secondary Material Properties Recommended for Bedding Sand for Vehicular Applications [ICPI, 2007].

MATERIAL PROPERTIES	TEST METHOD	RECOMMENDED MAXIMUM OR MINIMUM
PRIMARY PROPERTIES		
Gradation	ASTM C 33 CSA A23.1 (FA1)	Maximum 1% passing No.200 (0.075 mm or 0.080 mm) sieve
Micro-Deval Degradation	CSA A23.2.23A ASTM D 7428	Maximum 8%
Constant Head Permeability	ASTM C 2434	Minimum 0.002 cm/s (2.83 in/h)
SECONDARY PROPERTIES		
Soundness - Sodium Sulfate or Magnesium Sulfate	ASTM C 88	Maximum 7%
Silica (Quartz and Quartzite)/ Carbonate Ratio	MTO LS-616 ASTM C 295	Minimum 80/20 Ratio
Angularity and Particle Shape	ASTM D 2488	Minimum 60% combined sub-angular and sub-rounded

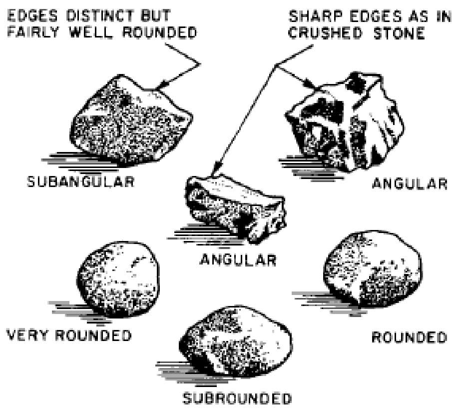

Figure 2. Description of coarse grains according to ASTM D2488.

Figure 3. Example of sand from the ICPI bedding sand test program with a total combined % of sub-angular and sub-rounded particles equal to 65% according to ASTM D 2488 [ICPI, 2004].

5. CONCLUSIONS

The paper presents a rationale for additional primary and secondary material properties beyond gradation that have been adopted as industry recommendations in North America. Primary properties include gradation, Micro-Deval and permeability, and secondary properties include magnesium or sodium sulfate soundness, petrography to confirm acceptable silica/carbonate ratios, and particle shape as defined by angularity. Project specifications in North America are starting to include these recommendations. When bedding sand does not conform to the properties in Table 4, it may be selected based on field performance. This basis for acceptance can be adequate if the sand is supplied from a consistent quarry source and the specifier or contractor can demonstrate successful historical field performance under similar traffic conditions. In these cases, the owner should specify the class of anticipated vehicular traffic and the contractor should verify past field performance of the bedding sand under similar vehicular traffic.

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