Concrete Pavement Mixture Design and Analysis (MDA):

Effect of Aggregate Systems on Concrete Mixture Properties

National Concrete Pavement Technology Center

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16. Abstract

For years, specifications have focused on the water to cement ratio (w/cm) and strength of concrete, despite the majority of the volume of a concrete mixture consisting of aggregate. An aggregate distribution of roughly 60% coarse aggregate and 40% fine aggregate, regardless of gradation and availability of aggregates, has been used as the norm for a concrete pavement mixture. Efforts to reduce the costs and improve sustainability of concrete mixtures have pushed owners to pay closer attention to mixtures with a well-graded aggregate particle distribution. In general, workability has many different variables that are independent of gradation, such as paste volume and viscosity, aggregate's shape, and texture. A better understanding of how the properties of aggregates affect the workability of concrete is needed.

The effects of aggregate characteristics on concrete properties, such as ability to be vibrated, strength, and resistivity, were investigated using mixtures in which the paste content and the w/cm were held constant. The results showed the different aggregate proportions, the maximum nominal aggregate sizes, and combinations of different aggregates all had an impact on the performance in the strength, slump, and box test.

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Concrete Pavement Mixture Design and Analysis (MDA): Effect of Aggregate Systems on Concrete Mixture Properties

Technical Report
July 2012

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INTRODUCTION

For years, specifications have focused on the water to cement ratio (w/cm) and strength of concrete, despite the majority of the volume of a concrete mixture consisting of aggregate. An aggregate distribution of roughly 60% coarse aggregate and 40% fine aggregate, regardless of gradation and availability of aggregates, has been used as the norm for a concrete pavement mixture.

Efforts to reduce the costs and improve sustainability of concrete mixtures have pushed owners to pay closer attention to all aspects of their concrete mixtures. This has led many owners to specify concrete mixtures with a well-graded aggregate particle distribution. This mixture tries to blend coarse, intermediate, and fine aggregates to pack as much aggregate in a mixture while minimizing the paste volume.

Shilstone has been a longtime supporter of optimized graded concrete, and he purports that these mixtures have improvements in durability, strength, and resistance to abrasion and erosion. Shilstone believed an optimized gradation of concrete would help control the workability, pumpability, and response to vibration of concrete (Shilstone 1989).

Shilstone developed a graphical method to design a concrete mixture based on his experiences that used volumes and gradations of the coarse, intermediate, and fine aggregates as shown in Figure 1. The graphical method used equations called the Coarseness Factor and Workability Factor (Shilstone 1990). In the Shilstone chart, different zones were thought to correspond with different application's workability.

When designing optimized concrete, many current Department of Transportations (DOTs) reference the middle of the Shilstone chart or Zone 2 as the best location for a mixture design. While this seems logical, no actual data supports this. Even Shilstone suggested that paving mixtures do not need the same workability as other mixtures, and therefore values with lower workability factors could be used (Richard 2005). Mixtures with a lower workability factor are located near the bottom of the Shilstone chart.

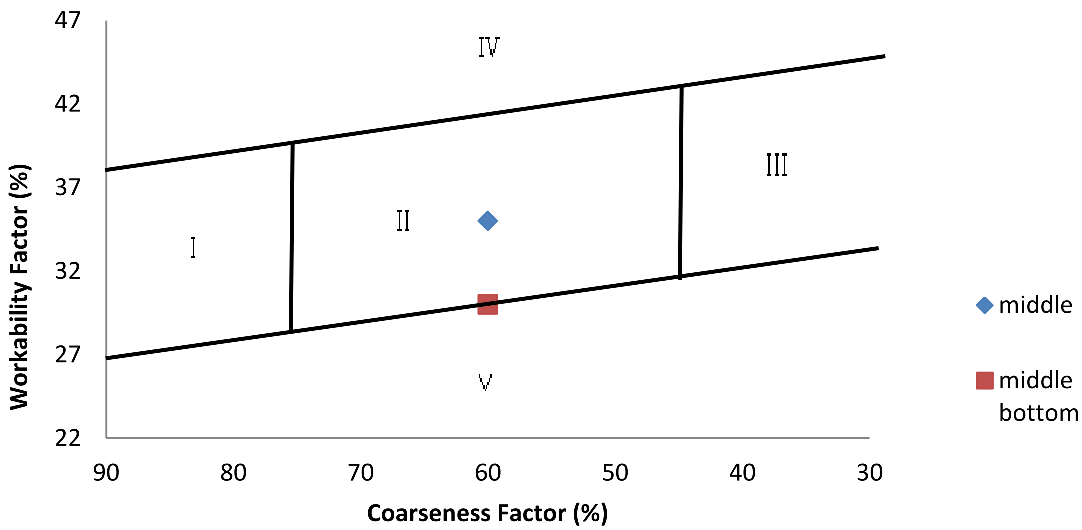


Figure 1. Shilstone chart

Coarseness Factor (CF) = (Q/R)*100

Workability Factor (WF) = W + (2.5(C-564)/94)

Q= cumulative % retained on the 3/8 sieve
R= cumulative % retained on the no. 8 sieve
W= % passing the no. 8 sieve
C= cementitious material content in lb/yd^3

Compass is a mixture proportioning software developed by the Transtec Group for the Federal Highway Administration (FHWA), which uses data from sieve analysis and specific gravities in packing models to estimate the voids content (The Transtec Group 2004). Conventional wisdom says that by reducing the voids in the mixture, the designer is also reducing the volume of paste that is needed. The Toufar method was used in this research because the batch proportions were found to be the most reasonable when compared to the other two packing methods.

In general, workability has many different variables that are independent of gradation, such as paste volume and viscosity, aggregate's shape, and texture. A better understanding of how the properties of aggregates affect the workability of concrete is needed.

The design of concrete mixtures is rarely controlled by the strength of the mixture. Instead, mixtures are designed to have a certain workability that matches the construction technique used for the placement. For a concrete pavement, a slip form paver uses vibrators to consolidate a low slump concrete that extrudes out of the back of the machine. While the slump test (ASTM C 143) has been the most common technique to evaluate the workability of a mixture, it fails to be sensitive to changes in the mixture at very low levels of workability. Paving concrete must be able to be placed and consolidated by the paver and not lose its edge as it leaves the paver. The best way to evaluate the performance of a mixture is to use a paver with the material. Unfortunately, no current lab test exists to evaluate the ability to place and consolidate a pavement mixture. Since a paver uses a vibrator as the focal point of consolidation, a test to evaluate the response of a mixture to a vibrator has been developed and is presented. The research team realizes that the developed test may not truly replicate the complicated processes of a concrete paver, but they feel that this test does give an indication of the mixture's response to vibration.

MATERIALS

The river rock and manufactured sand were from Texas and the crushed limestone and river sand were from Oklahoma. Table 1 gives a coarse and fine aggregate description.

A sieve analysis for each of the aggregates was completed in accordance with ASTM C 136. Each of the aggregates has a maximum nominal aggregate size, as shown in Table 2.

Absorption and specific gravity of each aggregate followed ASTM C 127 for a coarse aggregate or ASTM C 128 for a fine aggregate. In Table 2 and Figure 2, the properties and sieve analysis of each aggregate are provided.

The lignosulfonate mid-range WR met ASTM C 494. All the concrete mixtures described in this paper were prepared using a Type 1 cement that meets the requirements of ASTM C 150. The oxide analysis is shown below in Table 3. No fly ash was used in the testing.

Table 1. Aggregate description

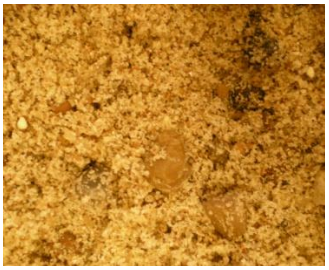
Aggregate	Photo of Aggregate	Description
Crushed Limestone		Combination of low and high sphericity with a mid-angularity
River Gravel		Combination high and low sphericity with a well-rounded angularity
River Sand		Fines with very few intermediate particles
Manufactured Sand		Angular fines with intermediate particles

Table 2. Properties and sieve analysis of each aggregate type

		Aggregate Type							
		1.5 in. Nominal Max Coarse		3/4 in. Nominal Max Coarse		3/8 in. Intermediate		Fine	
		Limestone*	River Rock	Limestone*	River Rock	Limestone*	River Rock	River Sand	Man Sand*
Properties	Fineness Modulus	5.71	3.32	3.32	3.76	5.92	5.81	2.55	2.94
	Bulk Specific Gravity (SSD)	2.74	2.64	2.70	2.65	2.72	2.62	2.65	2.63
	Absorption(%)	0.45	1.55	0.66	1.26	0.58	1.95	0.55	0.70
Percent Passing the Sieve Number	1.5 in.	95.5	96.8	100	100	100	100	100	100
	1 in.	28.1	59.5	100	96.2	100	100	100	100
	3/4 in.	5.2	49.0	94.4	77.5	100	100	100	100
	1/2 in.	0.3	30.6	48.2	36.3	100	100	100	100
	3/8 in.	0.1	18.1	22.8	13.5	93.3	99.8	97.5	100
	#4	0.1	4.6	3.1	0.2	11.3	17.6	96.7	91.8
	#8	0	3.2	0.0	0.0	1.5	0.7	95.0	82.7
	#16	0	0	0	0	0.7	0.2	83.0	74.6
	#30	0	0	0	0	0.5	0.1	52.7	56.7
	#50	0	0	0	0	0.5	0.1	17.2	12.4
	#100	0	0	0	0	0.3	0.1	3.3	2.4
	Pan	0	0	0	0	0	0	0	0

*note: limestone was crushed limestone and man sand was manufactured sand

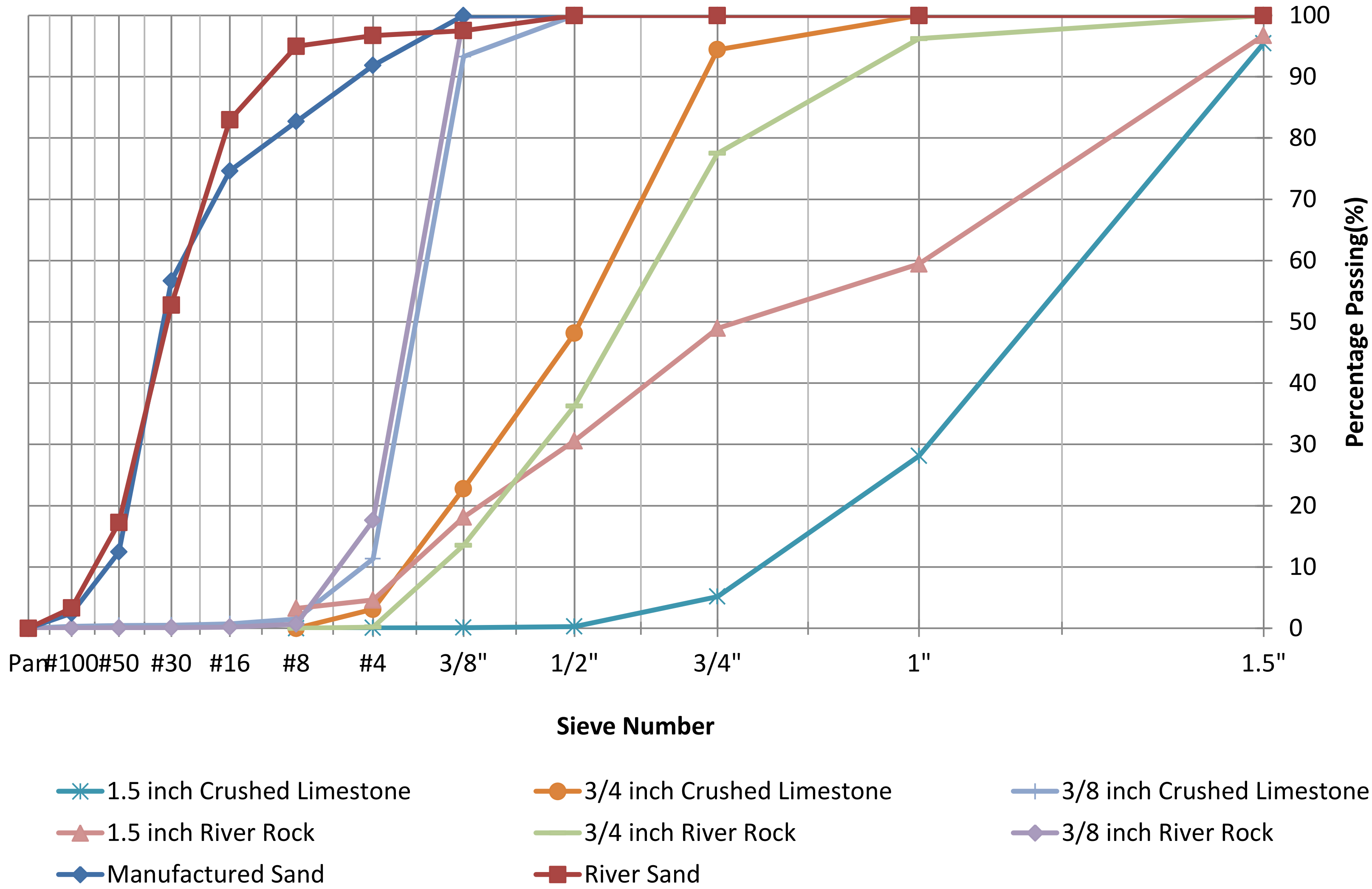


Figure 2. Sieve analysis for each aggregate type

Table 3. Cement oxide analysis: Type 1 cement

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	C_3S	C_2S	C_3A	C_4AF
21.1%	4.7%	2.6%	62.1%	2.4%	3.2%	0.21%	0.34%	56.7%	17.8%	8.2%	7.8%

Mixture Design

Each mixture had the equivalent of five sacks (470 lbs) of cement per cubic yard of concrete and 211.5 lbs of water. The w/cm was held constant at 0.45 and therefore the paste content at 7.03 ft^3/yd^3, or 26% of the mixture's volume.

Each aggregate pair was evaluated using five different gradations. These included combinations that were at the center and bottom center of the Shilstone chart, with minimum voids contents as determined by the Toufar method within Compass (The Transtec Group 2004), a mixture close to the power 45 line, and mixture with 60% of the largest aggregate size and 40% of the fine aggregate size.

Table 4 gives a summary of the gradations. Figure 2 shows a comparison of the gradations of individual aggregates. In Figures 3 through 10, a comparison is made of the gradations for the individual aggregates and the mixtures investigated. A separate figure is created for each aggregate combination investigated.

These experiments were designed to intentionally hold the paste constant and vary the gradations of the mixtures. This allowed the impact of aggregate gradations on the workability and response to vibration, as well as the strength of the mixtures to be investigated. This will allow different methods of aggregate gradation design to be directly compared.

Table 4. Gradation description.

Gradation	Description
Middle of Shilstone	Located in the middle of the Shilstone chart in Zone 2 as shown in Figure1. The middle of Shilstone has a coarseness factor of 60 and a workability of 35.
Bottom of Shilstone	As shown in Figure 1 with the coarseness factor of 60 and workability of 30, the bottom middle is located in Zone 2 on the Shilstone chart.
60% CA, 40% FA	With no intermediate aggregate added, the gradation uses 60% of coarse aggregate and 40% of the fine aggregate by volume.
Power 45	Gradation follows the power 45 line.
Minimum Voids	The gradation that produces the minimum voids content as per the Toufar Method implemented by Compass.

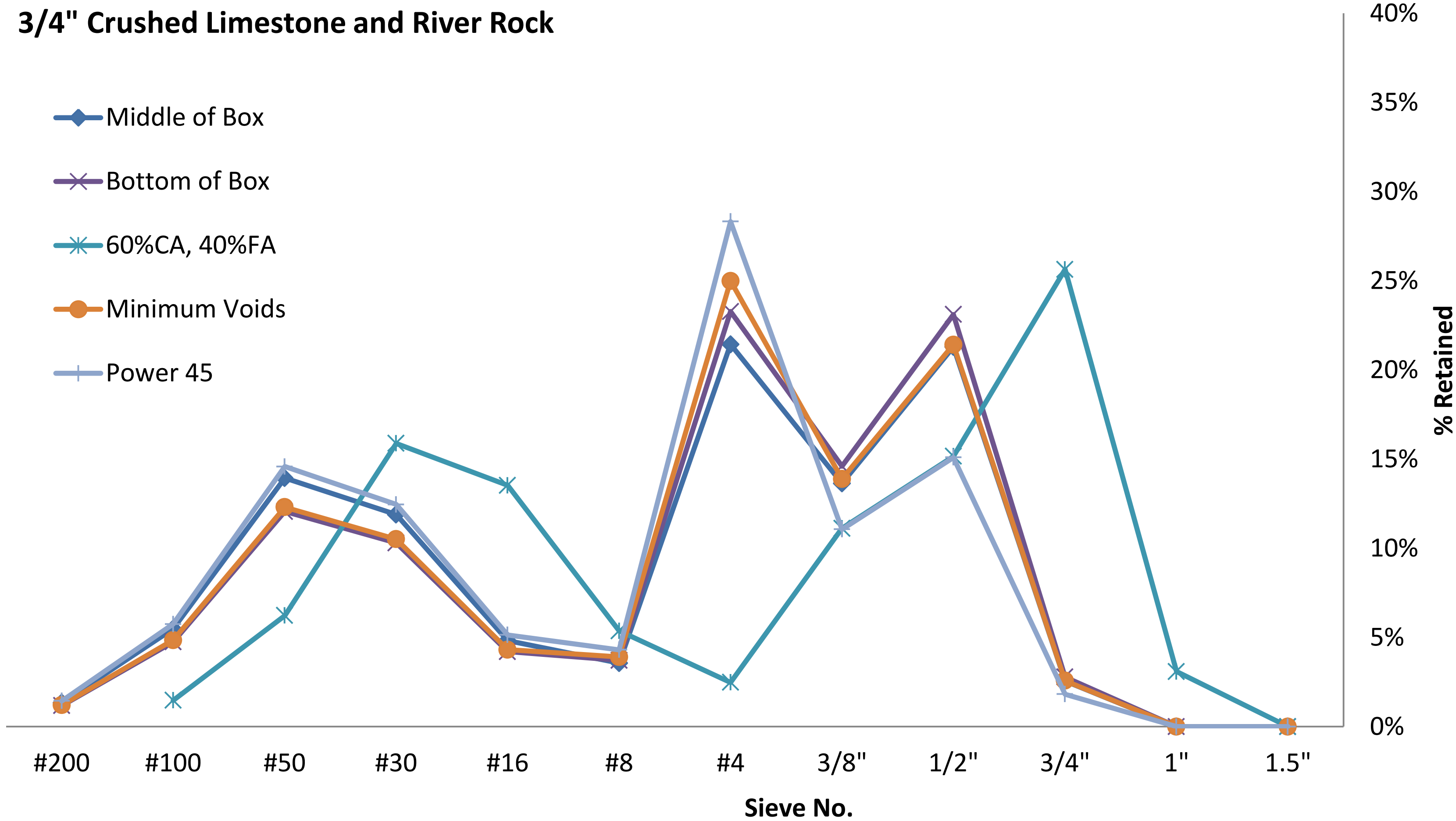


Figure 3. Sieve analysis for 3/4 in. crushed limestone and river sand

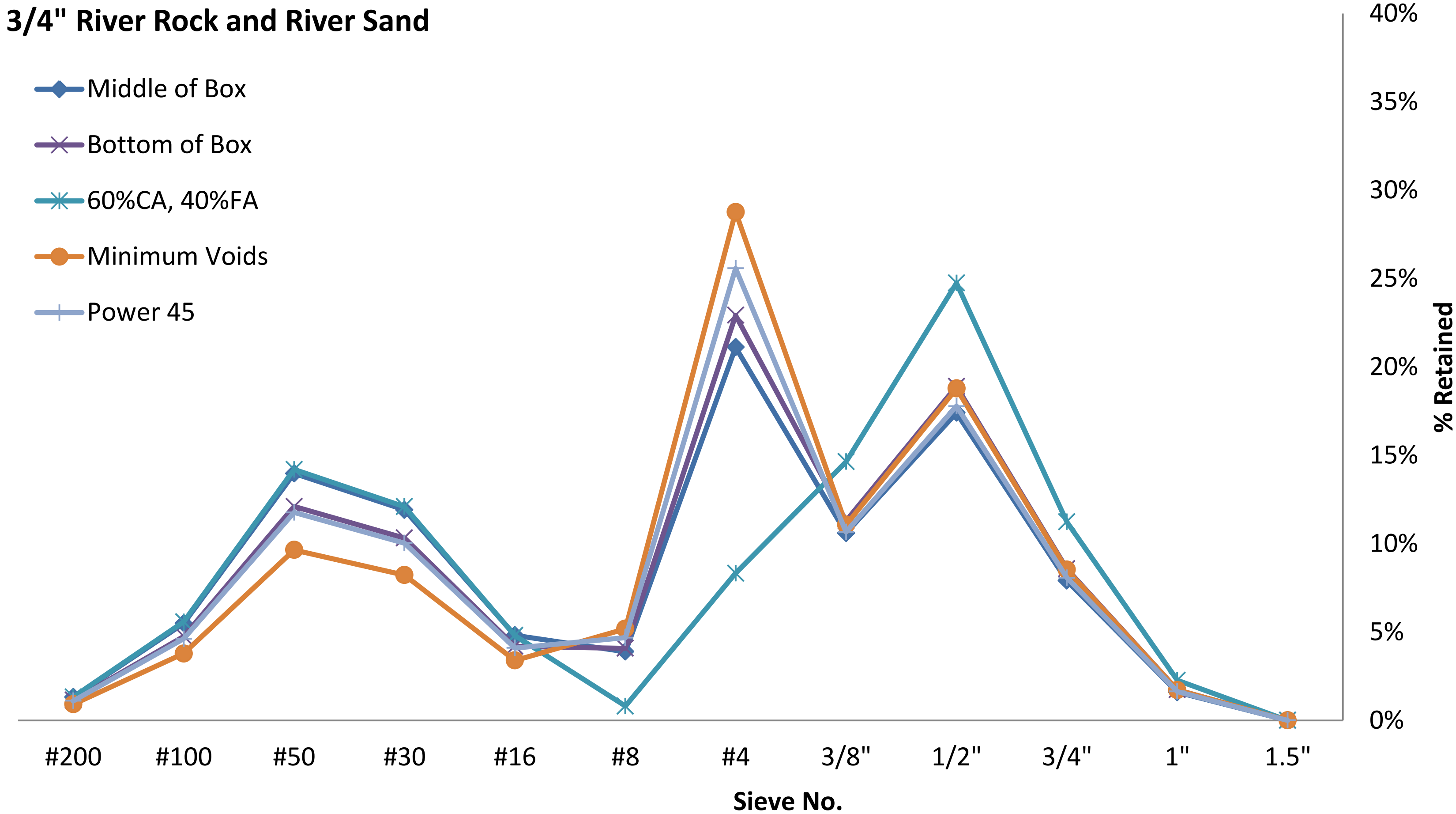


Figure 4. Sieve analysis for 3/4 in. river rock and river sand

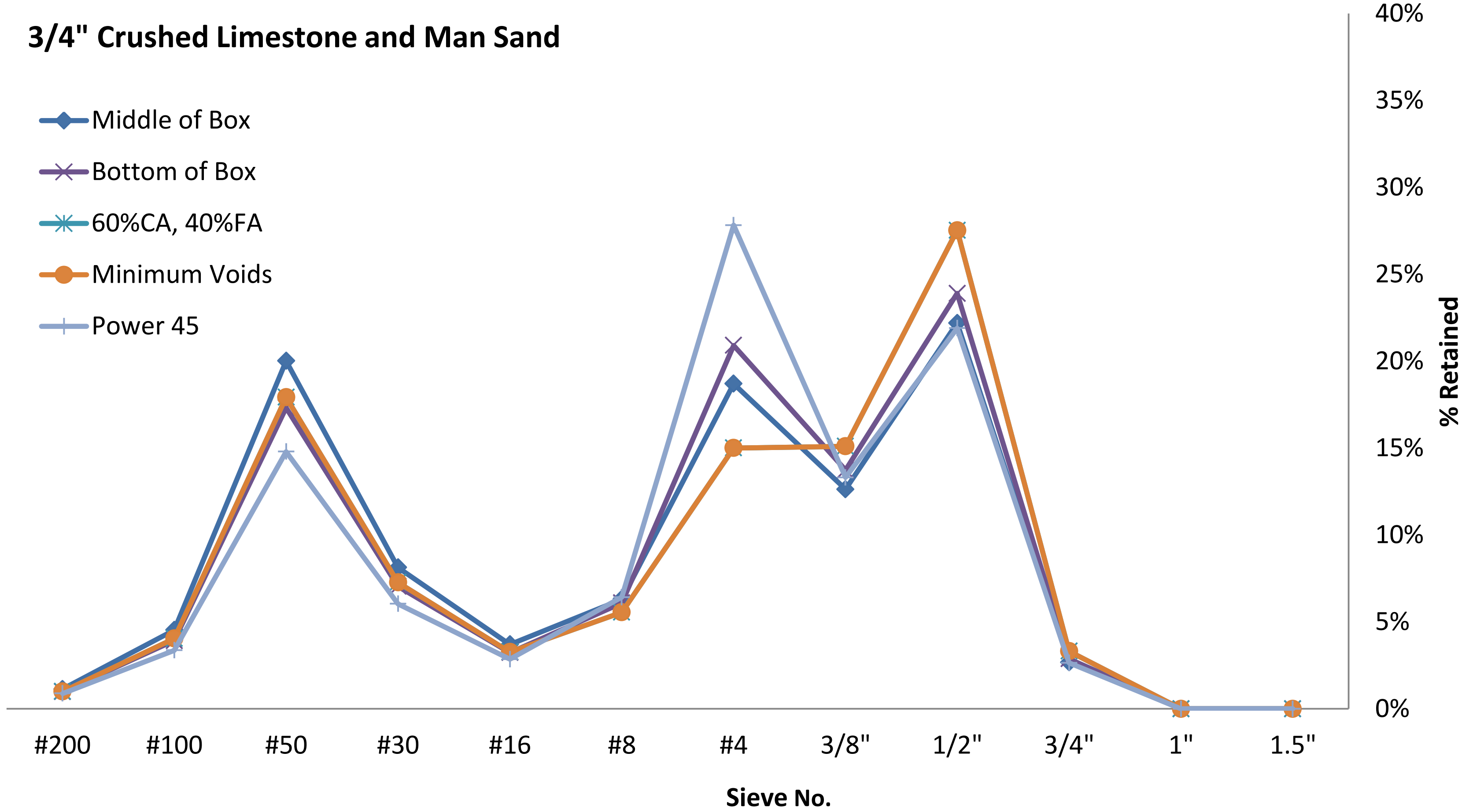


Figure 5. Sieve analysis for 3/4 in. crushed limestone and manufactured sand

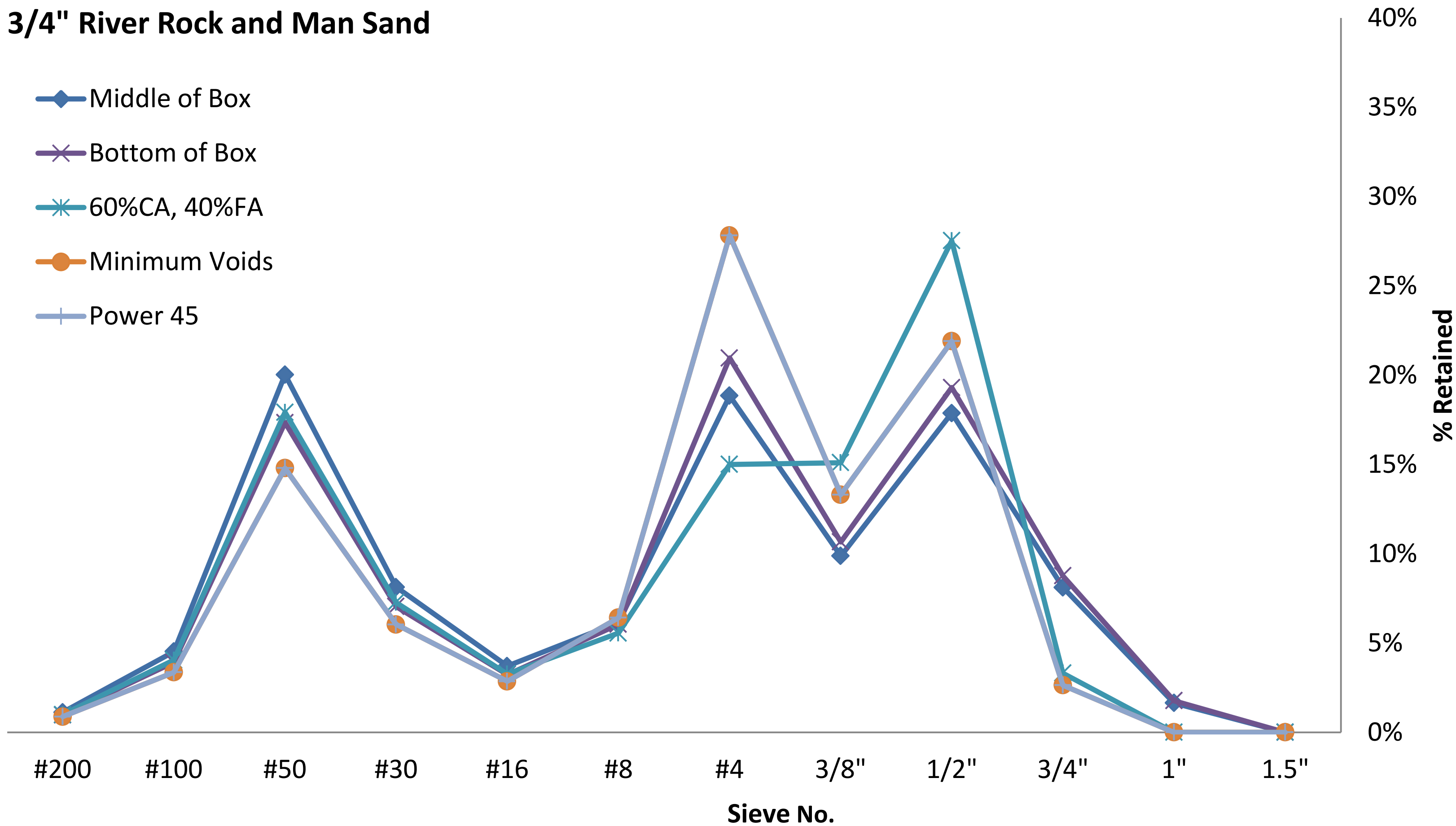


Figure 6. Sieve analysis for 3/4 in. river rock and manufactured sand

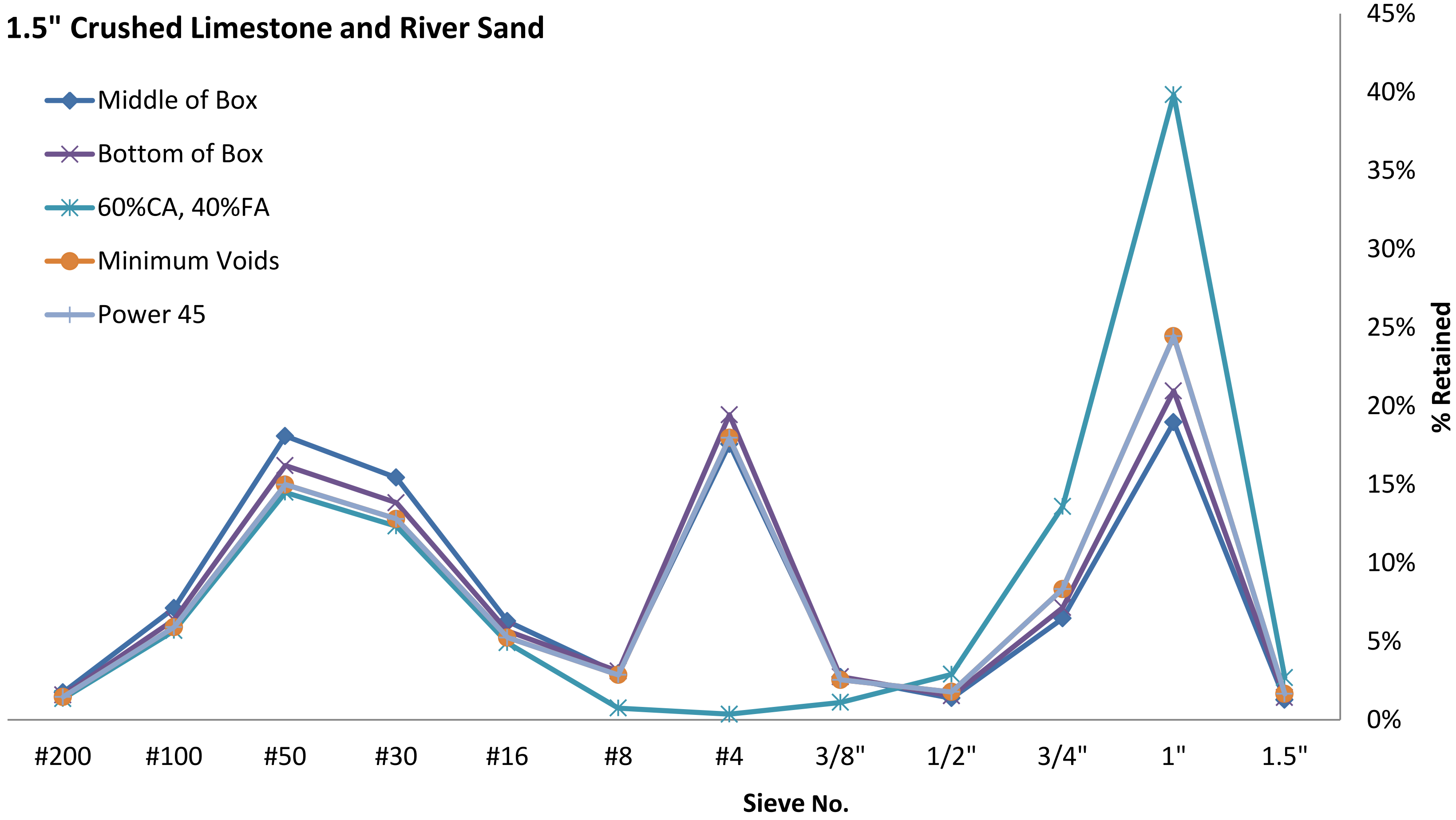


Figure 7. Sieve analysis for 1.5 in. crushed limestone and river sand

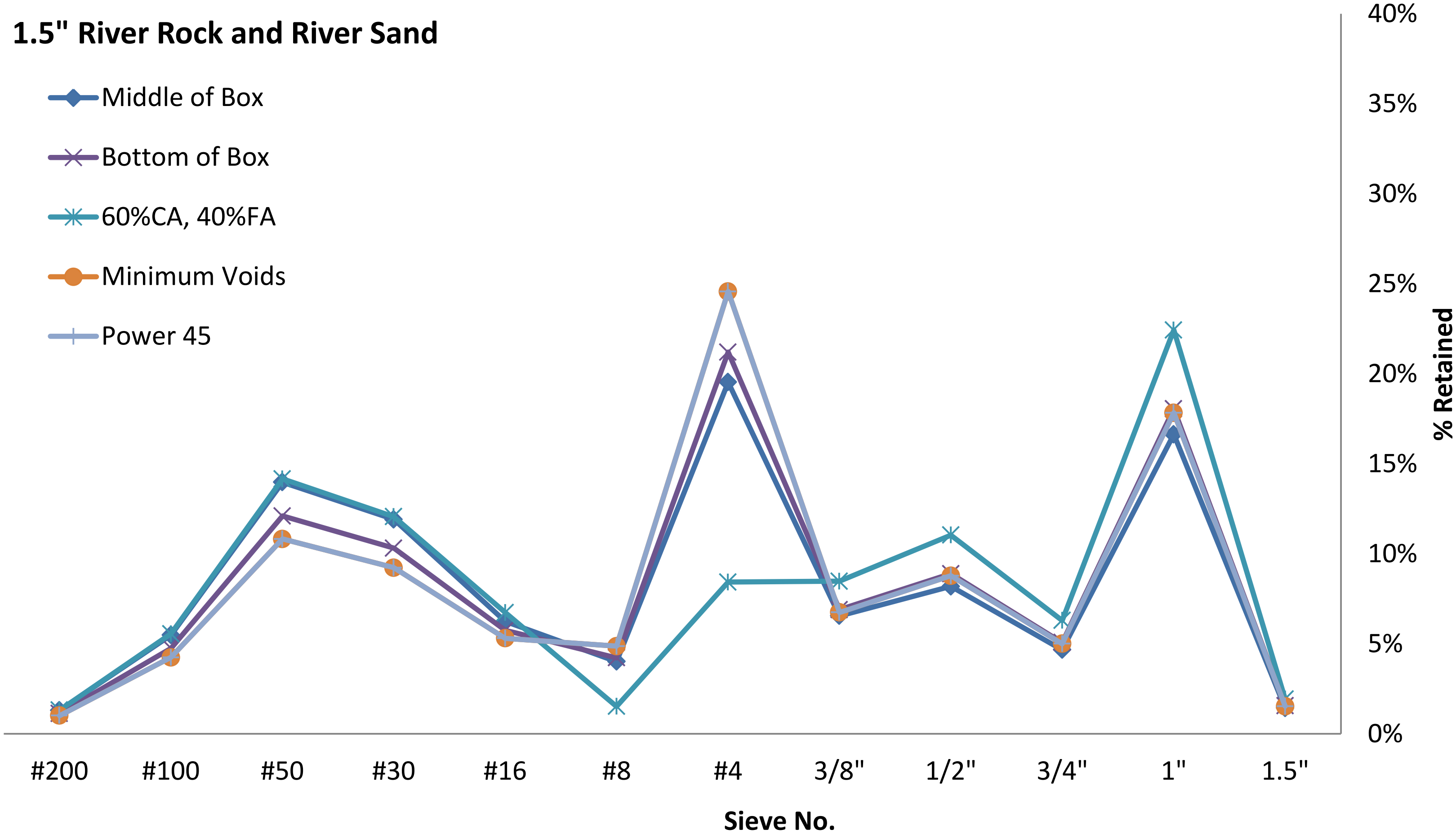


Figure 8. Sieve analysis for 1.5 in. river rock and river sand

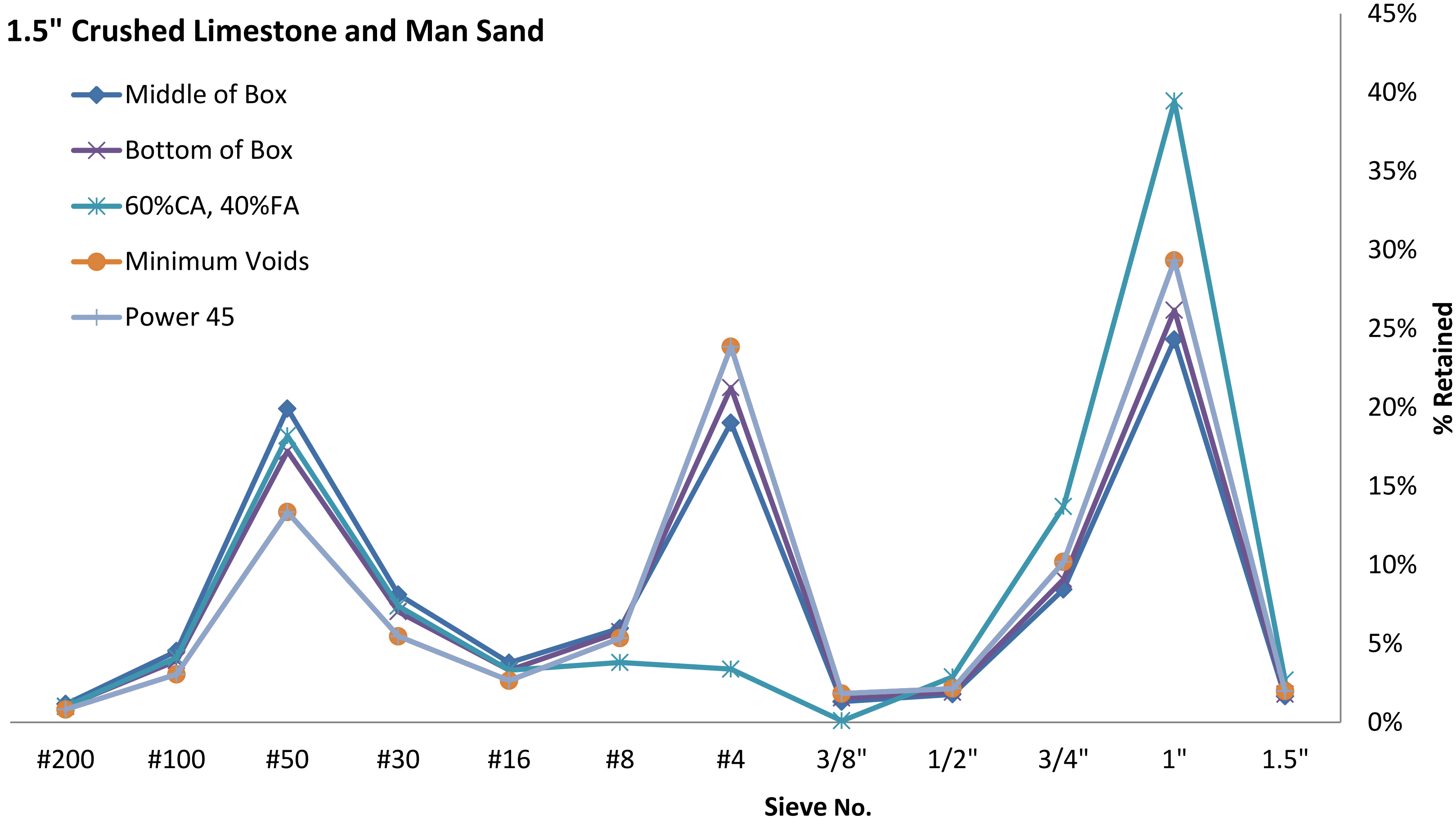


Figure 9. Sieve analysis for 1.5 in. crushed limestone and manufactured sand

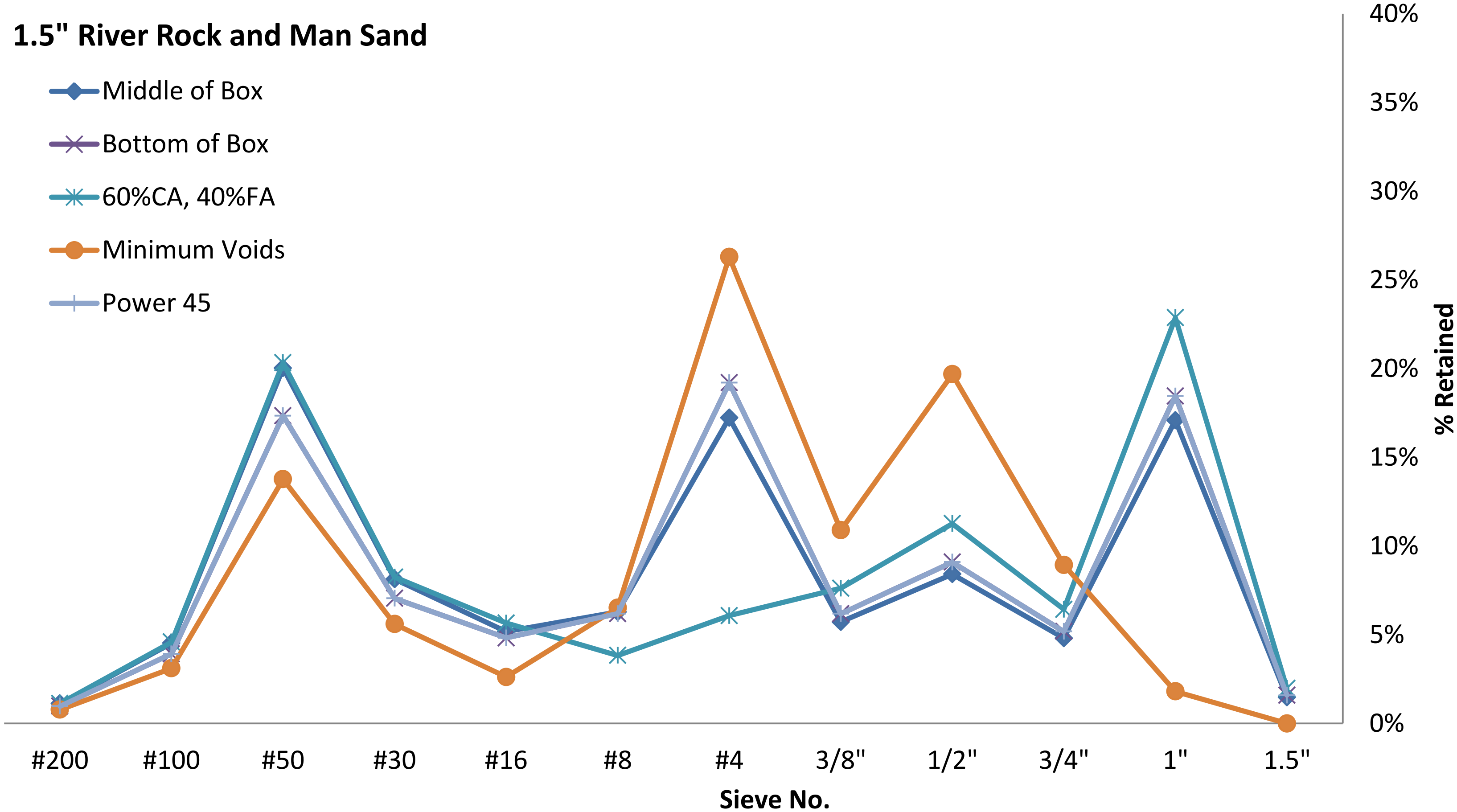


Figure 10. Sieve analysis for 1.5 in. river rock and manufactured sand

Concrete Mixture and Testing Procedures

Aggregates are collected from outside storage piles and brought into a temperature-controlled laboratory room at 73°F (23°C) for at least 24 hours before mixing. Aggregates were placed in a mixing drum and spun, and a representative sample was taken for a moisture correction. At the time of mixing, all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed.

Next, the cement and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was turned on and mixed for three minutes. The initial testing of the mixture included air content (ASTM C 231), slump (ASTM C 143), unit weight (ASTM C 138), and a novel test method to examine the response to vibration called the box test.

Box Test

The box test evaluated the performance of a mixture's response to vibration. This was done by taking a controlled volume of concrete and measuring the amount of surface voids after vibration. A vibrator uses stress waves to separate air from the mixture and force the mortar into the voids. If the concrete has large amounts of surface voids after vibration then the mortar was not able to flow to this surface and the mixture was declared to be unacceptable.

The box test used a 1/2 in. plywood base and 1 ft^2 sides with clamps to hold the box together. Figure 11 shows the different pieces of the box test.

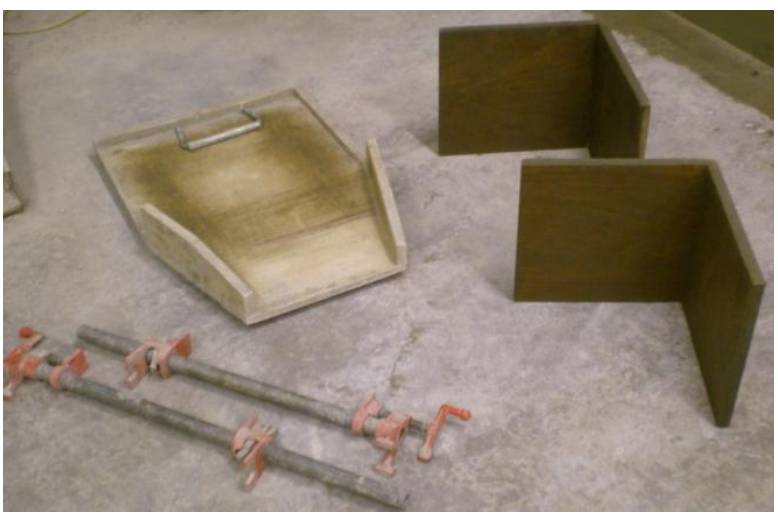


Figure 11. Items in the box test

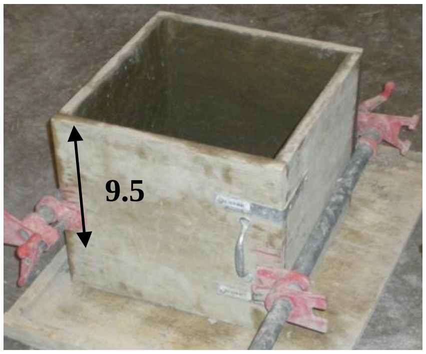
Placed on the base, a 1 ft^3 wooden formed box was constructed and held together by clamps as shown in Figure 12. Concrete was uniformly hand-scooped without consolidation into the box up to a height of 9.5 in. Care was taken to not consolidate the concrete during placement.

Figure 12. Box dimensions

A handheld 1 in. head WYCO model number 922A electric vibrator with a measured speed of 8000 vibrations per minute was used to consolidate the concrete by inserting it at the center of the box. The vibrator was lowered over three seconds to the bottom of the box and then raised over three seconds.

The clamps were removed from the side of the box and the side walls were removed. Each step of the process was shown in Table 5.

Table 5. Box test

 **Step 1** Construct box and place clamps tightly around box. Hand scoop mixture into box until the concrete is 9.5 in.	 **Step 2** Vibrate downward for 3 seconds and upward for 3 seconds.
 **Step 3** Remove vibrator.	 **Step 4** After removing clamps and the forms, inspect the sides for surface voids and edge slumping.

The response of the mixture to vibration was evaluated by comparing the sides of the box to the ranking scale in Table 6. An average score was found for the box test. A ranking of 2 was determined to be sufficient to pass the box test.

Observations were recorded about the sphere of influence of vibrator and any imperfections left on the surface by the vibrator. Figure 13 shows where the vibrator gave no sphere of influence and left a hole. Figure 14 shows that the vibrator had a 5 in. radius sphere of influence that left the corners unconsolidated. In Figure 15, the vibrator had a sphere of influence that reached the entire concrete sample, and the edges were straight.

Table 6. Box test ranking scale

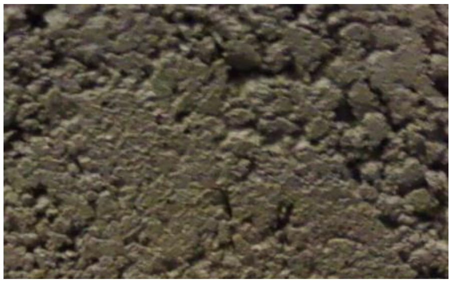
 **4** Sides held an edge, but had over 50% overall amounts of surface voids.	 **3** Sides had a between 30-50% overall surface voids. Corners were not consolidated.
 **2** Sides and corners had between 10 and 30% overall amounts of surface voids.	 **1** Sides had less than 10% overall amount of surface voids.

Figure 13. No sphere of influence

Figure 14. Sphere of influence almost to corners

Figure 15. Mixture passed the box test

If the concrete was found to fail the box test, the material used in the slump test and the box test was placed back into the mixer. The material used to test the air content was discarded as water was added. The mixer was turned on and charged with a mid-range water-reducing agent and mixed for three minutes. By adding the mid-range, the viscosity of the mixture was decreased, or the workability was increased.

After mixing the slump, unit weight and box test was conducted again. The air content was not tested again until the mixture was found to pass the box test. This was done to hold the mixture volume constant throughout the addition of the WR. If the box test failed again, slump, unit weight, and box test material was placed back into the mixer, charged with more mid-range water-reducing agent, and mixed for three minutes.

The process of adding water-reducing agent, testing slump, unit weight, and box test continued until the mixture passed the box test. Since the mixture has a limited time frame before initial set, if the mixture exhibited a loss in slump, or surpassed 45 minutes from initial mixing, the mixture was discarded.

At the point of the process where the box test passed, the air content was tested. The slump and box test material was placed back into the mixer and agitated for 30 seconds. Finally, 4x8” concrete specimens were made according to ASTM C 192. The concrete specimens were tested at 7- and 28-day strength using ASTM C39 and with the surface resistivity meter or Wenner probe. On the longitudinal side of the saturated cylinder, the Wenner probe measured the resistivity at eight different places. During the testing, the Wenner probe broke causing some data not to be collected.

Varying the WR dosage of the mixture until a mixture is able to show satisfactory performance in the box test provided a quantitative method to compare the different aggregate gradations. Since more WR was required in certain mixtures, these mixtures would not be as desirable as mixtures that did not need as high a dosage of WR. This was a useful method of comparison for this research.

Many of the admixture dosages investigated were higher than would be recommended in practice. This suggests that the paste content should be increased in these mixtures. This was not done as it was not the goal of this work to develop concrete mixtures, but instead to compare the performances of different aggregate gradations with a constant paste content.

RESULTS

Tables 7 and 8 are a compilation of the results from the fresh and harden properties of the mixtures completed. Table 9 compares the electrical resistivity of each mixture to the WR dosage to pass the box test. Figures 16 through 23 compare the Shilstone chart to each mixture’s WR dosage required to pass the box test. Figures 24 through 28 compare the WR dosage needed to pass the box test, compressive strength at 7 and 28 days, and the slump of the mixture when it passed the box test for the different investigated gradations.

Table 7. Results of the mixtures with 3/4 in. maximum nominal aggregates

	Aggregate		Gradation				
	Coarse Fine	Properties	Shilstone Center	Shilstone Bottom	60/40	Power 45	Compass Min Voids
3/4" nominal maximum size aggregate	Crushed Limestone River Sand	WR (oz/cwt)	20.8	19.2	21.3	85.9	31.0
		Slump (inches)	0.50	1.75	1.00	0.50	1.25
		7 day fc (psi)	5160	4270	5080	6240	5040
		28 day fc (psi)	5820	5370	5930	8250	6340
		Air Content	2.5%	2.4%	3.2%	2.7%	2.9%
		Unit Wt	152.1	150.6	150.2	151.1	152.6
		Coarse	1553	1684	2015	1100	1561
		Intermediate	508	554	0	907	656
		Fine	1280	1107	1321	1338	1129
		CF WF	60 35	60 30	76.3 40	46.2 36.9	56.7 30.7
	River Rock River Sand	WR (oz/cwt)	15.3	17.9	17.2	18.6	6.7
		Slump (inches)	1.75	2.00	1.75	2.25	1.25
		7 day fc (psi)	4110	4710	4250	4850	4390
		28 day fc (psi)	4950	5220	5020	5100	4970
		Air Content	4.9%	3.4%	4.6%	3.4%	2.1%
		Unit Wt	147.8	148.7	147.3	149.4	151.0
		Coarse	1396	1516	1981	1427	1508
		Intermediate	597	650	0	770	885
		Fine	1302	1127	1321	1096	899
		CF WF	60 35	60 30	85.3 35.5	55.8 29.1	54.2 23.5
	Crushed Limestone Man Sand	WR (oz/cwt)	23.0	35.6	32.2	31.8	31.8
		Slump (inches)	0.75	1.00	1.75	0.75	0.75
		7 day fc (psi)	4800	4920	4250	5010	5010
		28 day fc (psi)	5860	5660	5070	6140	6140
		Air Content	6.8%	4.9%	8.5%	3.9%	3.9%
		Unit Wt	145.3	147.1	141.5	148.2	148.2
		Coarse	1627	1749	2015	1599	1599
		Intermediate	236	319	0	665	665
		Fine	1461	1262	1311	1075	1075
		CF WF	60 35	60 30	69.1 31	52.5 25.4	52.5 25.4
	River Rock Man Sand	WR (oz/cwt)	21.5	21.0	20.9	20.1	20.4
		Slump (inches)	1.00	1.50	1.50	1.50	1.75
		7 day fc (psi)	3880	3990	3870	4260	4300
		28 day fc (psi)	4450	4240	4110	4550	4660
		Air Content	7.8%	7.3%	8.0%	7.9%	5.0%
		Unit Wt	142.6	140.5	141.3	141.8	145.8
		Coarse	1438	1553	1994	1348	1584
		Intermediate	370	454	0	481	686
		Fine	1478	1280	1297	1455	1016
		CF WF	60 35	60 30	77.6 30.4	55.4 34.4	55.4 34.4

Unit weight was measured in lbs/ft³ and aggregate types were measured in lbs/yd³

Table 8. Results of the mixtures with 1.5 in. maximum nominal aggregates

1.5" nominal maximum size aggregate

Aggregate		Gradation				
Coarse Fine	Properties	Shilstone Center	Shilstone Bottom	60/40	Power 45	Compass Min Voids
Crushed Limestone River Sand	WR (oz/cwt)	32.0	34.0	13.7	31.8	31.8
	Slump (inches)	1.25	1.50	1.00	1.50	1.50
	7 day fc (psi)	5420	5250	4520	4700	4700
	28 day fc (psi)	5970	5470	5430	6020	6020
	Air Content	3.5%	3.1%	3.7%	3.8%	3.8%
	Unit Wt	150.6	151.7	149.8	148.7	148.7
	Coarse	1205	1306	2046	1258	1258
	Intermediate	894	972	0	736	736
	Fine	1266	1092	1322	1369	1369
	CF WF	60 35	60 30	98.2 25.1	65.1 26.7	65.1 26.7
River Rock River Sand	WR (oz/cwt)	22.2	26.6	26.1	25.1	25.1
	Slump (inches)	1.75	2.00	1.75	2.00	2.00
	7 day fc (psi)	5240	5160	4630	4980	4980
	28 day fc (psi)	5910	5990	5480	6070	6070
	Air Content	4.8%	3.2%	4.3%	2.3%	2.3%
	Unit Wt	147.8	150.0	147.6	151.2	151.2
	Coarse	1470	1596	1978	1631	1596
	Intermediate	522	569	0	846	569
	Fine	1288	1116	1307	802	1116
	CF WF	60 35	60 30	80.8 35.4	56.3 26.6	56.3 26.6
Crushed Limestone Man Sand	WR (oz/cwt)	27.9	20.8	20.4	31.8	31.8
	Slump (inches)	1.0	1.5	1.5	1.5	1.5
	7 day fc (psi)	3870	4520	4140	4600	4600
	28 day fc (psi)	4300	5300	4980	6530	6530
	Air Content	8.3%	5.9%	5.4%	1.8%	1.8%
	Unit Wt	138.3	145.5	146.7	154.2	154.2
	Coarse	1263	1356	2044	1515	1515
	Intermediate	644	756	0	892	892
	Fine	1443	1244	1315	961	961
	CF WF	60 35	60 30	89.1 31.5	60.9 22.8	60.9 22.8
River Rock Man Sand	WR (oz/cwt)	19.5	19.3	21.0	19.3	25.9
	Slump (inches)	1.50	2.50	1.50	2.50	1.25
	7 day fc (psi)	4350	4080	4480	4080	4660
	28 day fc (psi)	4930	4740	5380	5630	5630
	Air Content	8.5%	3.7%	4.9%	2.3%	2.3%
	Unit Wt	141.4	149.3	146.7	151.0	149.3
	Coarse	1470	1596	1978	1596	1631
	Intermediate	522	569	0	569	846
	Fine	1288	1116	1307	1116	802
	CF WF	60 35	60 30	80.8 35.5	60 30	53.8 21

Unit weight was measured in lbs/ft³ and aggregate types were measured in lbs/yd³

Table 9. Wenner probe and WR dosage

	Aggregate Coarse Fine	Properties	Gradation: Shilstone Center	Shilstone Bottom	60/40	Power 45	Compass Min
3/4" nominal max size	Crushed limestone River Sand	7 day Wenner	5.8	4.4	5.6	4.0	5.3
		28 day Wenner	6.7	7.2	6.6	8.3	6.8
		WR (oz/cwt)	20.8	19.2	21.3	85.9	31.0
	River Rock River Sand	7 day Wenner	5.8	5.3	6.1	5.2	5.3
		28 day Wenner	6.8	6.5	6.8		
		WR (oz/cwt)	15.3	17.9	17.2	18.6	6.7
	River Rock Man Sand	7 day Wenner	5.5	5.8	5.3	5.1	5.8
		28 day Wenner					
		WR (oz/cwt)	21.5	21.0	20.9	20.1	20.4
1.5" nominal max size	Crushed Limestone River Sand	7 day Wenner	5.6	4.7	5.8		
		28 day Wenner					
		WR (oz/cwt)	32.0	34.0	13.7	31.8	31.8
	River Rock River Sand	7 day Wenner	4.9	4.6	4.6	4.9	4.9
		28 day Wenner					
		WR (oz/cwt)	22.2	26.6	26.1	25.1	25.1
	River Rock Man Sand	7 day Wenner	5.3	5.5	4.9	5.5	5.3
		28 day Wenner					
		WR (oz/cwt)	19.5	19.3	21.0	19.3	25.9

Wenner probe data reported in kOhms-cm

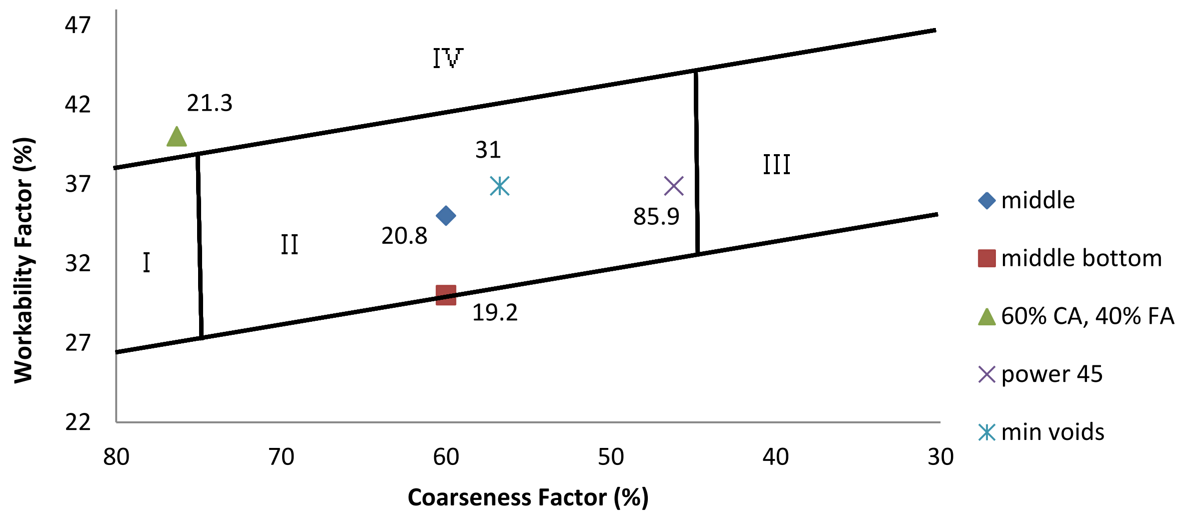


Figure 16. The results of the 3/4 in. crushed limestone and river sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

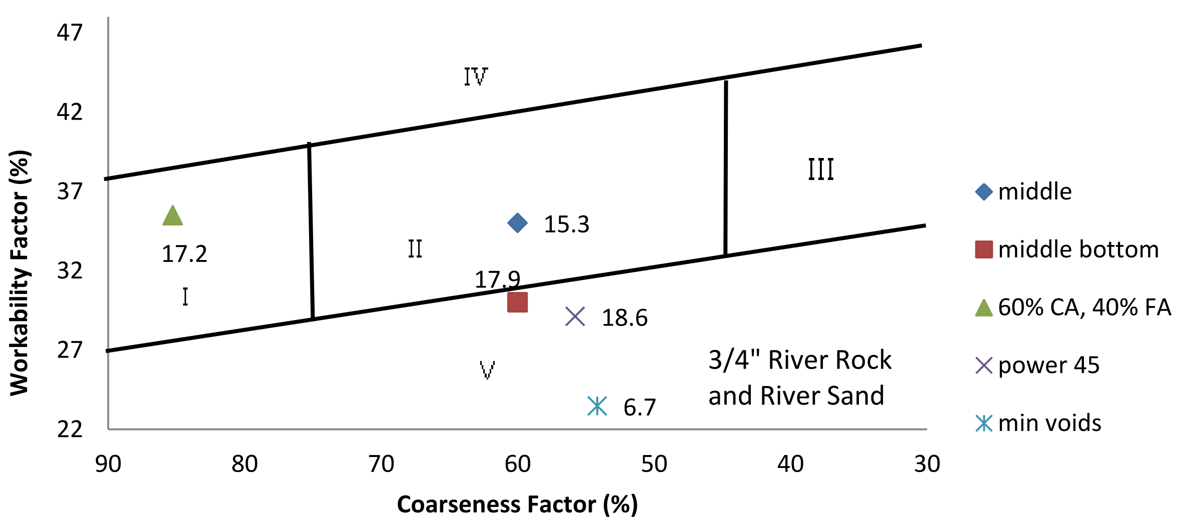


Figure 17. The results of the 3/4 in. river rock and river sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

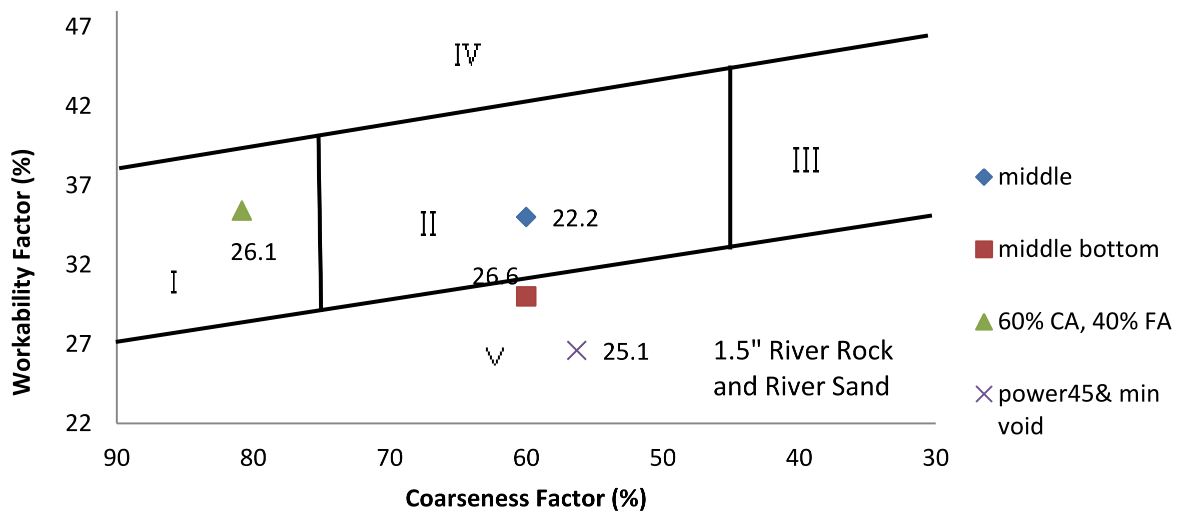


Figure 18. The results of the 1.5 in. river rock and river sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

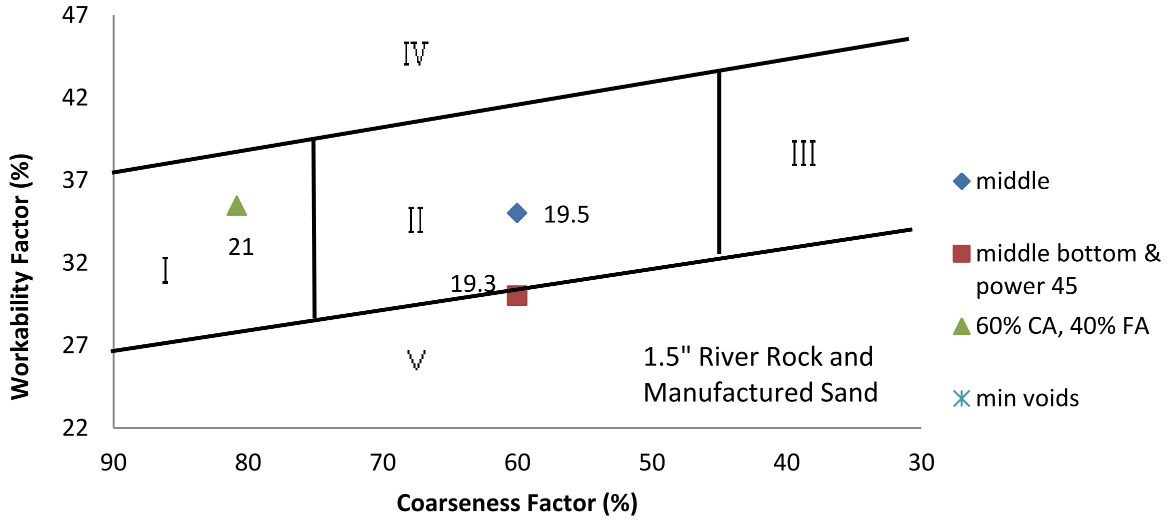


Figure 19. The results of the 1.5 in. river rock and man sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

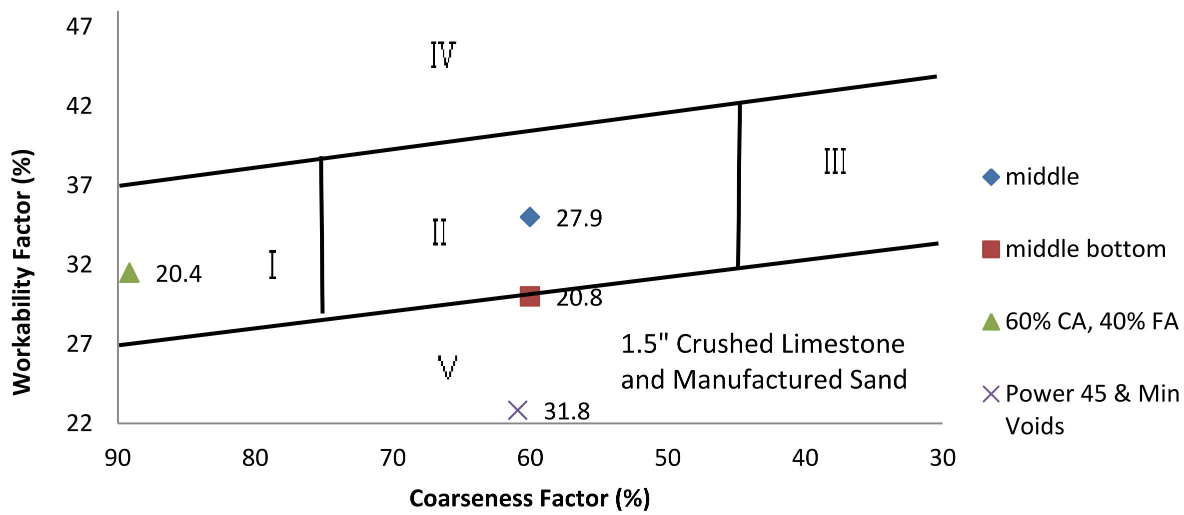


Figure 20. The results of the 1.5 in. crushed limestone and man sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

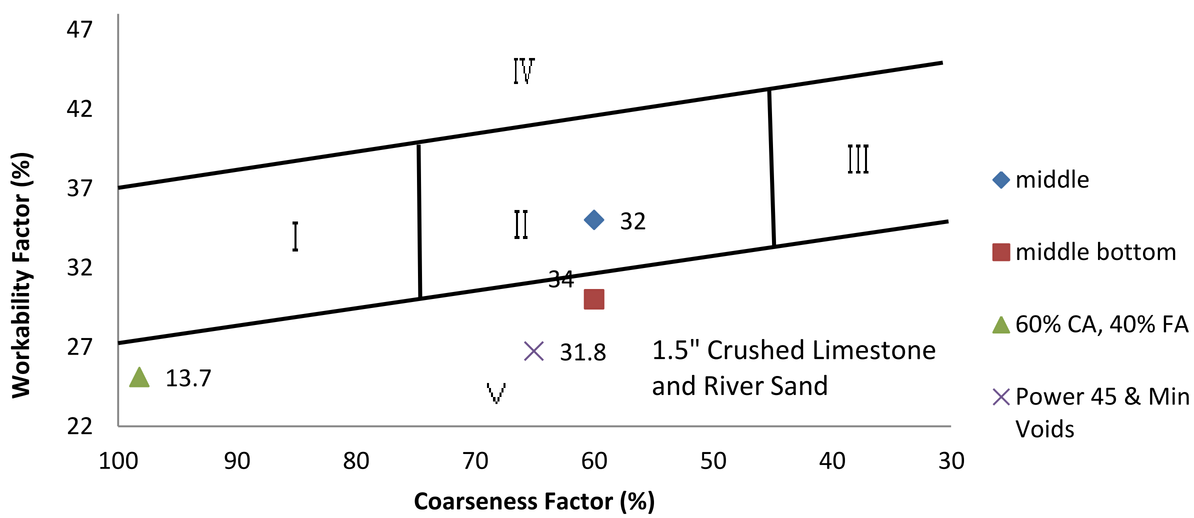


Figure 21. The results of the 1.5 in. crushed limestone and river sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

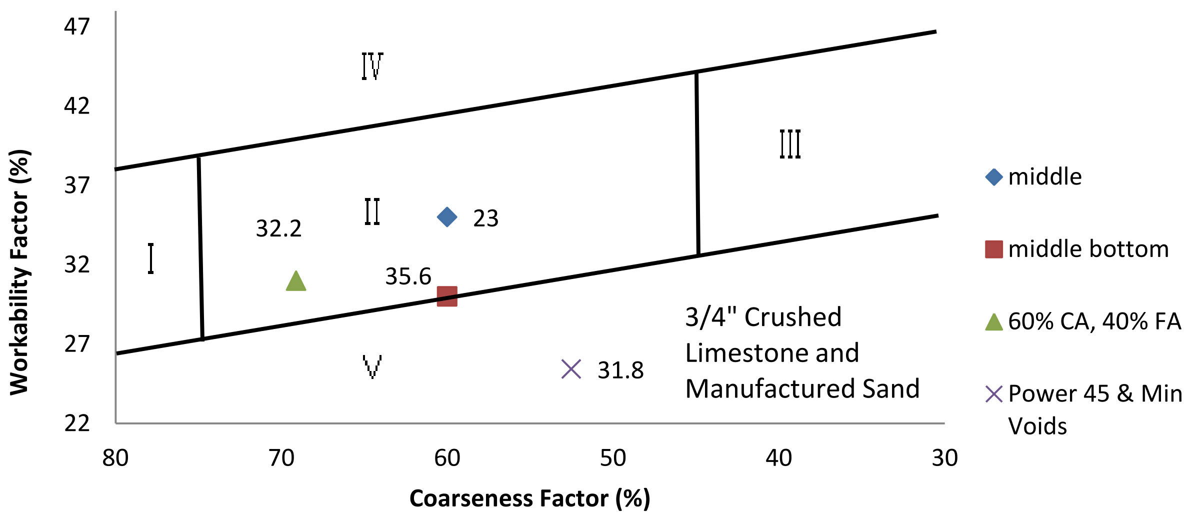


Figure 22. The results of the 3/4 in. crushed limestone and man sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

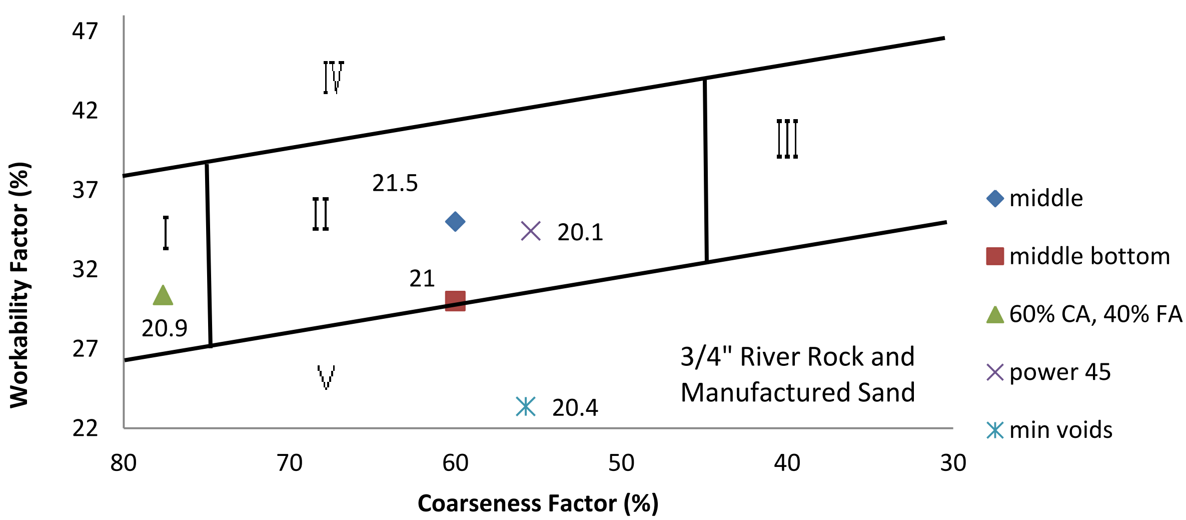


Figure 23. The results of the 3/4 in. river rock and man sand plotted on the Shilstone chart

The numbers shown are the WR (oz/cwt) required for the mixture to pass the box test.

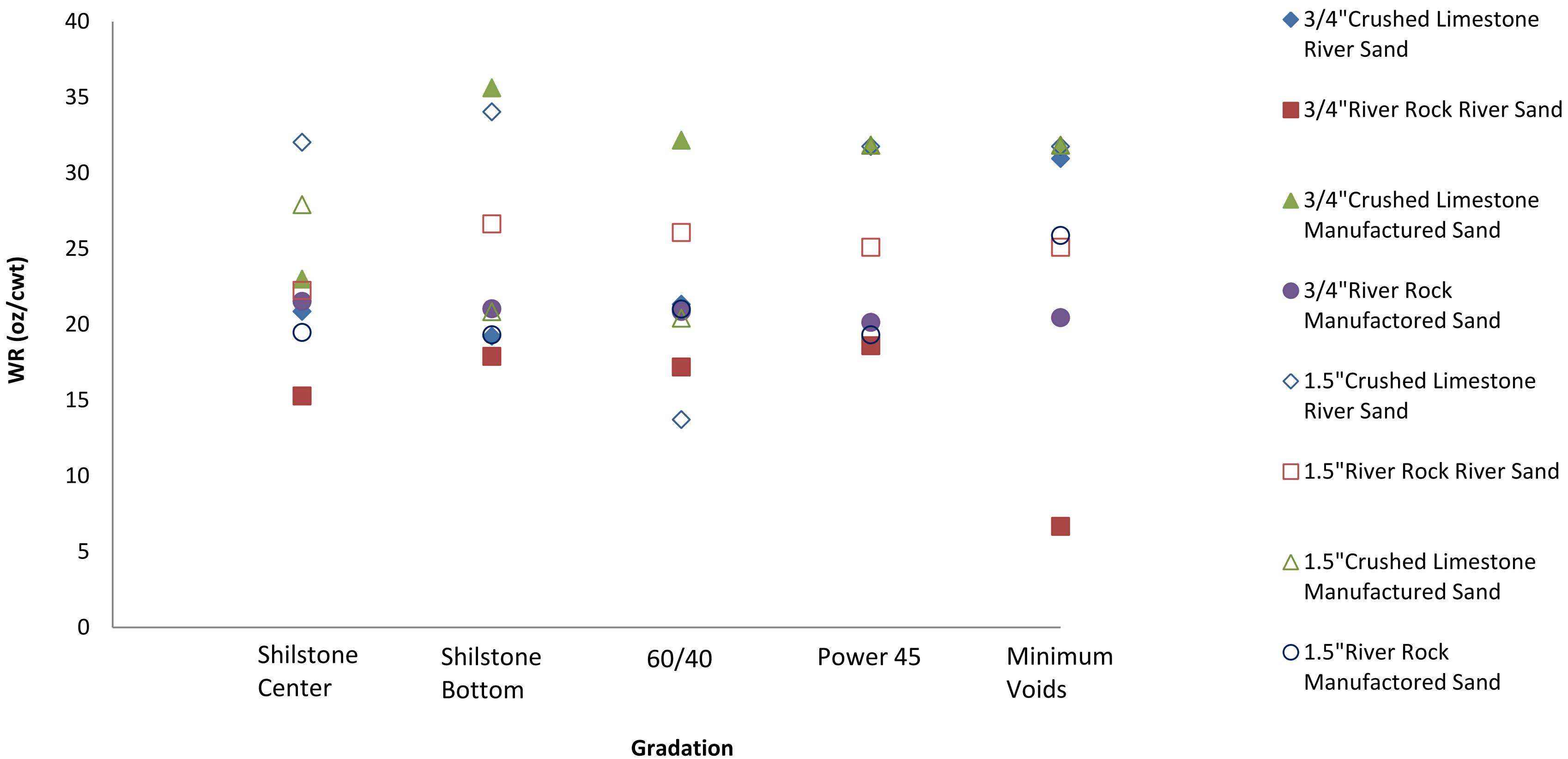


Figure 24. Gradation compared to the amount of WR to pass the box test

Note: 3/4 in. crushed limestone and river sand with a power 45 had an 85.9 oz/cwt.

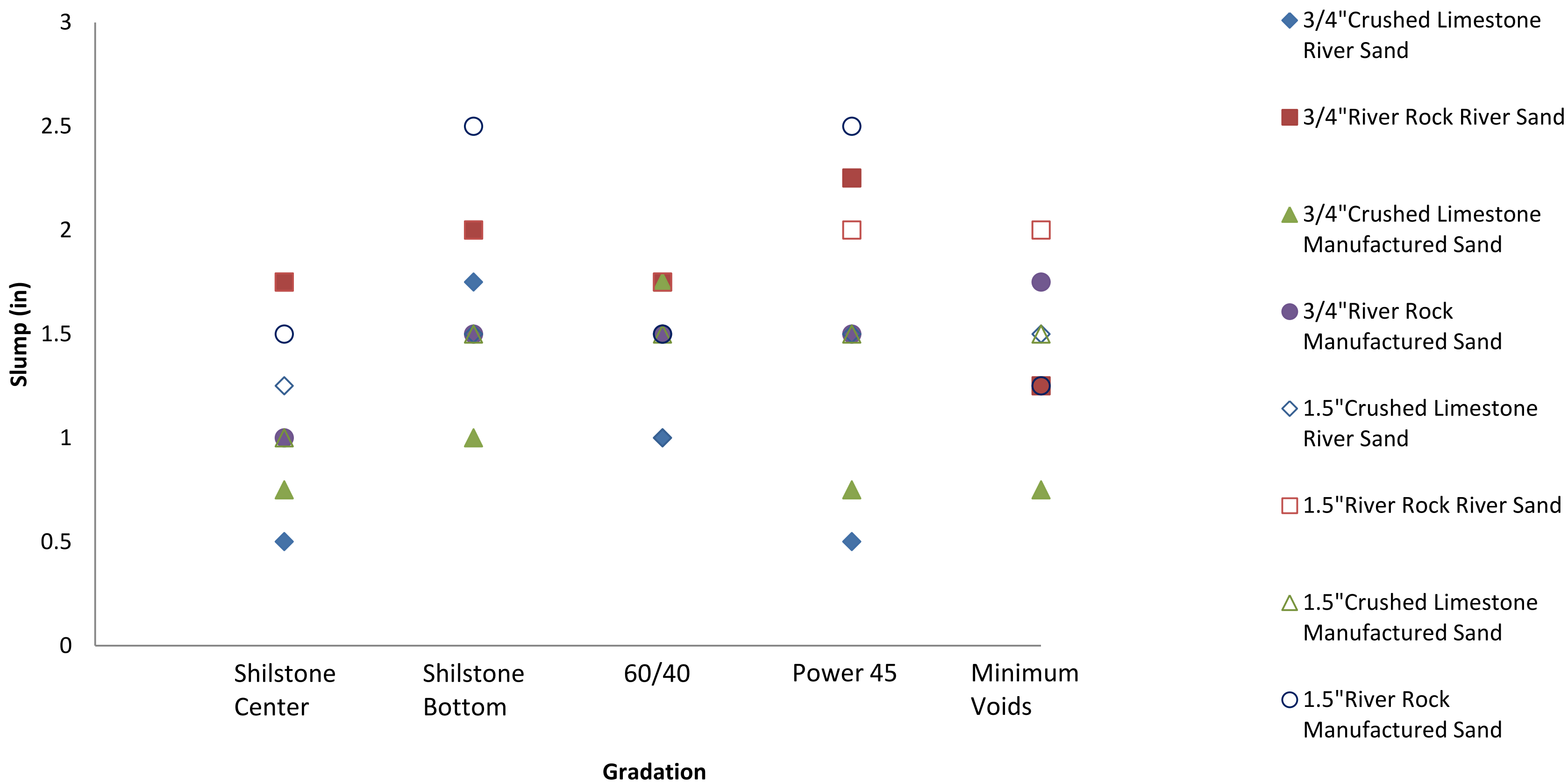


Figure 25. Gradation compared to slump measured when passing the box test

Note: 3/4 in. crushed limestone and river rock using river sand had the same slump.

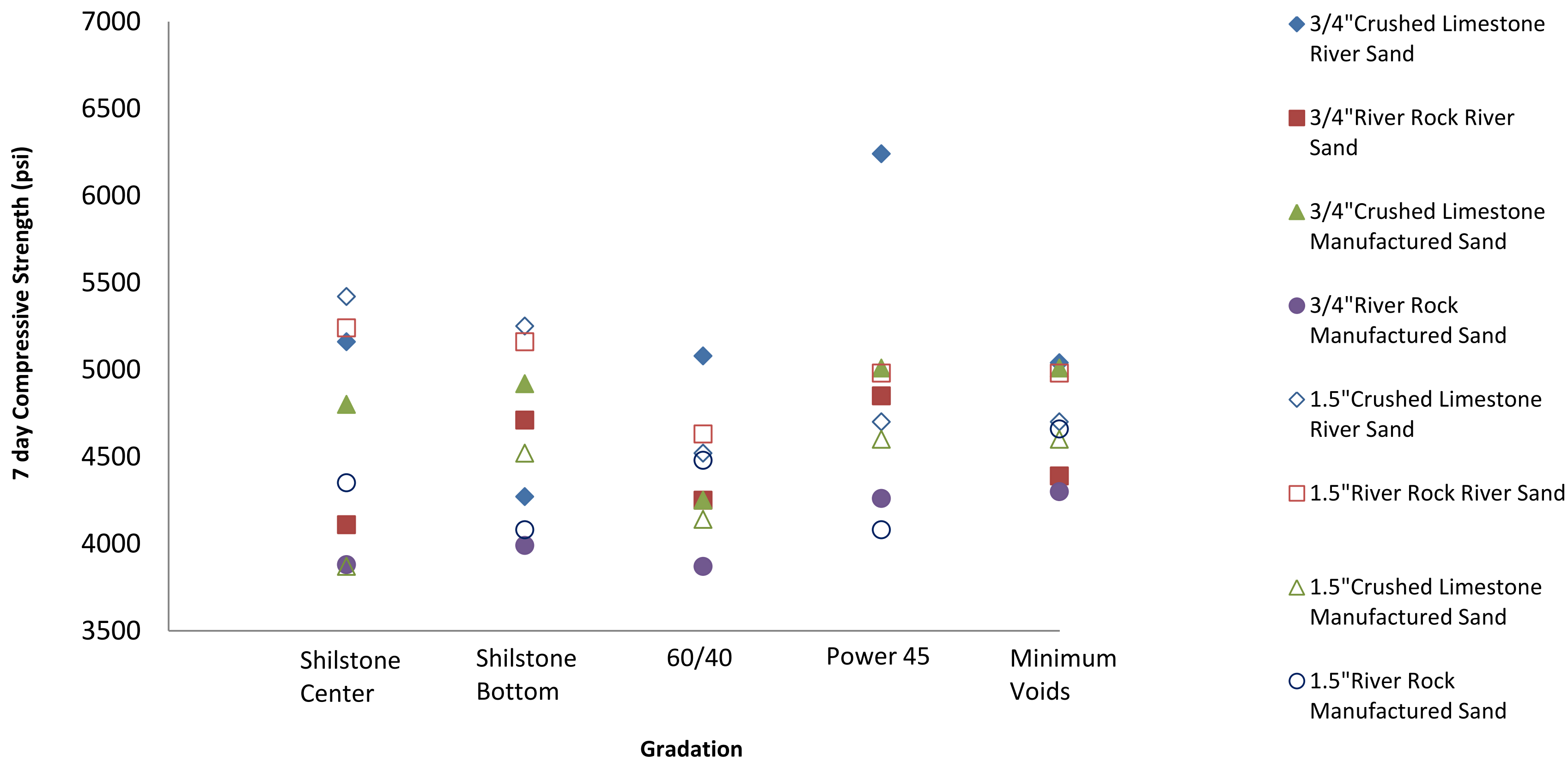


Figure 26. Gradation compared to the 7-day compressive strength

Figure 27. Gradation compared to the 28-day compressive strength

Note: 3/4 in. crushed limestone and river sand with a power 45 had a 28-day compressive strength of 8250 psi.

DISCUSSION

After each mixture passed the box test, the slump ranged between 0.5 in. and 2.5 in., which corresponds to slumps found in conventional pavement. The results from the slump and box test did not always correlate. Shown graphically in Figure 25, the 1.5 in. river rock and manufactured sand had a 2.25 in. slump, but could not pass the box test while 3/4 in. crushed limestone and river sand passed the box test with a 0.5 in. slump. When the same 3/4 in. crushed limestone and river sand was used with a gradation that matched the power 45, the mixture required 85 oz/cwt of WR for the mixture to pass the box test and the slump was only 0.5 in.

It was found that different slumps were required for different aggregate gradation strategies to pass the box test. For example when looking at the gradations for mixtures in the middle of the Shilstone chart with different aggregates, the slump ranged from 0.5 in. to 1.75 in., while the WR dosage varied from 15.3 to 32 oz/cwt to pass the box test.

These results reinforce that the box and slump test measure two different phenomena. While the box test measures the response to vibration, the slump test only measures the movement of the concrete downward from its own weight. Shilstone (1989) had the following to say:

> "The highly regarded slump test should be recognized for what it is: a measure of the ability of a given batch of concrete to sag."

Depending on the application for the concrete, the slump or box test may be useful to evaluate the performance. For slip-formed pavement applications, we feel that the response to vibration or the box test is more useful. However, the slump test may be better for hand-placed mixtures.

This non-uniform behavior between the tests is intriguing and suggests that one should not assume that concretes of the same slump will respond the same way to vibration and vice versa with mixtures that respond well to vibration. Instead, it is important to understand what properties of the mixture proportions, aggregate gradation, and characteristics lead to these differences in performance. It is clear that more work is needed.

Looking at Figure 25, several general trends can be observed with different aggregate types. In order to pass the box test, the river rock required a higher slump than the crushed limestone. All combinations of the 1.5 in. coarse aggregate required a higher slump than the 3/4 in. coarse aggregate to pass the box test.

For the aggregates and gradations investigated, the Shilstone chart was not able to predict how a mixture would perform in the box test. For example, in Figure 23, the five mixture gradations using 3/4 in. river rock and manufactured sand were in different locations on the Shilstone chart, but needed similar amounts of WR to pass the box test. In general, aggregate combinations in the middle of the Shilstone chart were able to pass the box test with the lowest slump. As shown in Figure 24, in five of the eight aggregate combinations there was no difference in WR required to pass the box test for gradations in the middle of the Shilstone chart and the mixtures with 60%

coarse and 40% fine aggregate. This suggests that including the intermediate aggregates in the concrete mixture did not have a consistent impact on the WR results of the box test. However, mixtures at the middle of the Shilstone chart had the ability to hold an edge, while the 60% coarse and 40% fine aggregate had a noticeable edge slump.

Several gradations were separated by an aggregate weight difference of only one hundred lbs/cy, but performed completely different. Shown in Tables 7 and 8, the 3/4 in. crushed limestone and river rock gradation of minimum voids and bottom of the Shilstone chart generate very similar weight amounts of sand, intermediate, and coarse aggregates, but used a difference of 11.8 oz/cwt. On the other hand, 3/4 in. river rock and manufactured sand gradation of power 45 and bottom of the Shilstone chart produced very similar weight amounts of sand, intermediate, and coarse aggregates, but required only a slight difference in WR dosage. In fact, 3/4 in. river rock and manufactured sand receive similar WR dosages for all the gradations.

Useful visual observations about the ability to finish and shovel the mixtures were made during the sample creation, but were not easily quantified. The mixtures in the center of the Shilstone chart and with the 60/40 gradation were the easiest to place and finish. Also, mixtures with river rock flowed better in the mixer than those with crushed limestone. It should be noted that the power 45 with 3/4 in. river rock and sand required the least amount of WR used when compared to the other mixtures, as shown in Figure 24. However, this mixture was very stiff and would be very difficult to place and finish.

Looking at Figure 26, the mixtures using gradations with intermediate aggregates all had a 7-day strength over 3800 psi. The mixtures containing 1.5 in. river rock were stronger than those with 3/4 in. river rock. As shown in Figure 27, the minimum voids and/or power 45 had the highest compressive strength for each combination, while the 60/40 gradation mixtures had a consistently lower compressive strength. Both the middle and bottom of the Shilstone chart mixtures had compressive strengths that varied widely.

After failing the box test with a WR dosage above 85 oz/cwt, the 28-day strength of the power 45 mixture with 3/4 in. crushed limestone and river sand was higher than 8200 psi. The compressive strength of the mixture could be affected by the power 45 gradation or the high WR dosage. The extremely high dosage of WR delayed final set of the compression cylinders for five days. The set delay did not have an extreme impact on the 7-day compressive strength.

The concrete's resistance to an electric current was measured using the Wenner probe. Unfortunately, the Wenner probe broke during the testing time frame and was not able to be repaired. A new one was purchased and measurements were resumed after it arrived. Table 9 shows the Wenner probe results of the different aggregate combinations. Neither the WR, gradation, nor type of rock combinations had a noticeable variation in resistance from the limited amount of data available.

Using amounts more than 1200 lbs/cy of manufactured sand gave high air contents and low unit weights. Also, both 1.5 in. and 3/4 in. river rock and river sand combinations resulted in 4% or higher air content for the Shilstone middle of box and 60/40 gradation. The cause was not found during this testing.

CONCLUSIONS

The effects of aggregate characteristics on concrete properties, such as ability to be vibrated, strength, and resistivity, were investigated using mixtures in which the paste content and the water/cement ratio were held constant. The results showed the different aggregate proportions, the maximum nominal aggregate sizes, and combinations of different aggregates all impacted the performance in the strength, slump, and box test. Based on the data collected, the following have been found:

- The location in the Shilstone chart did not correlate to the response of a concrete mixture to vibration.
- Aggregate gradations in the middle of the Shilstone chart and 60/40 gradations consistently required the lowest dosage of WR to show satisfactory response to vibration.
- Little difference between the WR dosage required for satisfactory response to vibration between mixtures with gradations in the middle of the Shilstone chart and 60/40 gradation. This suggests that concrete that responds well to vibration is not strongly dependent on the presence of the intermediate aggregates in a mixture.
- By using intermediate sizes in a concrete mixture, the compressive strength increases.
- A distinct increase in the slump was observed with the majority of river rock compared to crushed limestone. The crushed limestone’s slump ranged from 0.5 in. to 1.5 in., while the river rock’s slump ranged from 1 in. to 2.5 in.

Next Steps

Better quantitative techniques are needed to evaluate the performance of a concrete mixture for different applications. For this work, the ability of the mixture to be vibrated and placed by a paver was investigated. This was done with a novel test method created by the research team. This work led to many improvements in the test and sparked future work that will continue to improve this important need.

The research team plans on investigating the box test by using accelerometers placed between the vibrator and the walls of the container. As the concrete is vibrated, the accelerometers should describe the rate of mortar movement. This would provide a more quantitative measurement than the current visual inspection of the box test. Also, the box test will be correlated with field performance of a slip-formed paver. These field correlations will help to better understand what limits should be placed on the test.

The findings in this work showed little difference in workability for mixtures with and without intermediate aggregate sizes and the same paste content. This implies that specifications requiring a contractor to use an intermediate aggregate size will not allow a reduction in paste volume over mixtures without these aggregates intentionally being added for paving mixtures if the goal is to find a mixture that will respond to vibration.

Data on other ongoing research suggests that the shape and texture of aggregates play an important role in their response to vibration. Unfortunately, these parameters are not currently measured in the design of concrete mixtures. More work is ongoing.

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Shilstone, James M., Sr., “Concrete Mixture Optimization,” *Concrete International*, American Concrete Institute, Farmington Hills, Michigan, June 1990, pages 33-39.

The Transtec Group, Inc. (2004). Concrete Mixture Performance Analysis System (Version 1.00.0022) [computer software]. Texas.

Standards and Specifications

ASTM C 39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 127, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 128, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 136, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 138, “Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 143/C 143M-03, “Standard Test Method for Slump of Hydraulic Cement Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 150, “Standard Specification for Portland Cement, American Society for Testing and Materials”, West Conshohocken, Pennsylvania.

ASTM C 192, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 231-04, “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

ASTM C 494-05, “Standard Specification for Chemical Admixtures for Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.