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Optimizing Aggregate Gradation to Reduce Concrete's Permeability

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13. Abstract
Concrete durability has become an increasingly important design parameter as state highway agencies look to increase the service life of concrete infrastructure. In this study, 60 concrete mixtures were prepared with different aggregate gradation techniques, different cementitious systems, and different amounts of cementitious materials to investigate their influence on concrete's durability. The results show that Tarantula gradation T-4, which has a lower aggregate void ratio, produced the highest formation factor (i.e., more than 2,000 after 56-day curing) and the second highest surface resistivity among all 20 mixtures designed with cementitious system 50TI/50S and the minimum amount of cementitious materials. The Power gradation P-3, designed with cementitious system 50TI/50S and the minimum amount of cementitious materials, produced the second highest formation factor (more than 1,800 after 56-day curing) and the highest surface resistivity among all 20 mixtures. It was also found that Tarantula gradation T-3 with the minimum amount of cementitious materials produced a slump value of zero, a very low 28-d compressive strength (i.e., less than 3,000 psi), and a very low formation

factor for all three cementitious systems. Among all three cementitious systems, 50TI/50S (50% portland cement and 50% slag cement) produced the highest surface resistivity and formation factor for most of the gradations at all four curing times (i.e., 14 days, 28 days, 56 days, and 90 days).

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Abstract

Concrete durability has become an increasingly important design parameter as state highway agencies look to increase the service life of concrete infrastructure. In this study, 60 concrete mixtures were prepared with different aggregate gradation techniques, different cementitious systems, and different amounts of cementitious materials to investigate their influence on concrete's durability. The results show that Tarantula gradation T-4, which has a lower aggregate void ratio, produced the highest formation factor (i.e., more than 2,000 after 56-day curing) and the second highest surface resistivity among all 20 mixtures designed with cementitious system 50TI/50S and the minimum amount of cementitious materials. The Power gradation P-3, designed with a cementitious system 50TI/50S and the minimum amount of cementitious materials, produced the second highest formation factor (more than 1,800 after 56-day curing) and the highest surface resistivity among all 20 mixtures. It was also found that Tarantula gradation T-3 with the minimum amount of cementitious materials produced a slump value of zero, a very low 28-d compressive strength (i.e., less than 3,000 psi), and a very low formation factor for all three cementitious systems. Among all three cementitious systems, 50TI/50S (50% portland cement and 50% slag cement) produced the highest surface resistivity and formation factor for most of the gradations at all four curing times (i.e., 14 days, 28 days, 56 days, and 90 days).

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Implementation Statement

The Tarantula or Power gradation techniques could be used to select the aggregate with the lowest aggregate void ratio to improve concrete's durability.

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Introduction

Concrete durability has become an increasingly important design parameter as state highway agencies look to increase the service life of concrete infrastructure. While there are several approaches to produce durable concrete (i.e., by reducing its permeability), one factor that often gets overlooked in a mixture design is the aggregate gradation. In practice, most concrete producers tend to use the grading limits specified in ASTM C33 for aggregates. However, the use of these limits may not necessarily produce durable concrete mixtures because the grading limits are too broad to guarantee optimum packing density. By maximizing the aggregate's packing density, the concrete's cement demand can be reduced, resulting in a less permeable concrete since cement paste is the most porous material in concrete. A high cement paste should also be avoided to minimize shrinkage and lower the environmental footprint of portland cement.

For these reasons, there is a need to optimize aggregate gradations for concrete mixture designs to maximize durability. This study focused on preparing concrete mixtures with optimal gradations based on five different aggregate gradation techniques in order to minimize permeability and cement demand without sacrificing workability. Durability tests through surface resistivity (AASHTO T 358) and formation factor (AASHTO 119-15 [Option A]) were conducted to test how different gradations perform versus the typical gap graded mixtures (per ASTM C33) that are prevalent in concrete field practice.

Literature Review

Aggregate gradation has long been recognized as an important parameter in concrete mixture design due to its influence on the mixture's workability, strength, and durability properties. However, in practice most concrete producers use the grading limits specified in ASTM C33 for aggregate gradation, which are too broad to guarantee the optimum packing density [1]. As such, researchers have explored alternatives to optimize aggregate gradation to deliver more durable concrete. It has been proposed that concrete mixtures should ideally have just enough cement paste to fill the voids between the aggregate particles, while at the same time separating them to reduce the inter-particle friction between the aggregates and achieve a good workability for the mixture [2]. For this reason, it is further proposed that a well-graded or densely graded aggregate structure could be adopted to minimize the voids between the particles, thus reducing the cement paste demand. By avoiding excess cement paste, it could make concrete less susceptible to shrinkage cracks, chloride penetrability, and potentially thermal cracking (particularly with mass concrete), ultimately increasing the durability of concrete [3].

In order to optimize the aggregate gradation in concrete mixture design, there have been several techniques developed in the past years, including the Shilstone chart, Power curve, 8-18 band [4, 5], and the newly proposed Tarantula curve by Cook et al. [3]. The Shilstone chart is also called Coarseness Factor Chart and consists of a coarseness factor as a horizontal axis and a workability factor as a vertical axis. There are five zones in the chart, with Zone I for gap-graded mixtures, Zones II/III for well-graded mixtures, Zone IV for mixtures with an excess of fine particles, and Zone C for mixtures with an excess of coarse aggregates [6]. The Power curve was developed in the early 1900s and is a curve of the passing percentage versus sieve size raised to the power of 0.45. The optimum gradation curve is the straight line between the origin and the maximum aggregate size [6]. The 8-18 Chart is based on the retaining percentage for each sieve size and is helpful in evaluating the excess or deficiency of aggregate at the specific sieve size [6]. Tarantula curve is an empirical method developed based on the 8-18 Chart with adjusted upper and lower limits for different aggregate sizes. It is noted that though Tarantula curve could help evaluate if a blend is good or not (i.e., within the curve limits or not), it could not help select which blend is optimal [6]. It is well noted that a 5-20 band is also specified in Louisiana Standard Specifications for Roads and Bridges [7].

For the minimum cement demand, Taylor et al. recommended that a volume ratio (V_{paste}/V_{voids}) of 125% to 150% is needed to achieve the minimum workability at a given gradation [8]. To measure workability, Taylor et al. [9] also suggested the use of a vibrating Kelly ball test in addition to slump to assess the responsiveness of a mixture to vibration, considering this property is highly desirable in highway construction applications such as slip form paving.

It is known that concrete is porous and includes pores at different sizes and different degrees of interconnectivity. Depending on the volume of pores and their interconnectivity, concrete would have different permeability, rendering to a different resistivity. For this reason, electrical resistivity, which measures the material's resistance to the passage of electrical charges, has been widely used as an effective tool to measure the permeability of concrete. Correlations have also been developed between the electrical resistivity of concrete and its water/rapid chloride permeability [10, 11, 12]. Further research shows that the ion concentration also plays an important role in the testing results of concrete's resistivity. However, electrical resistivity testing could not address the influence of pore solution. In order to solve this problem, formation factor is therefore introduced by dividing the concrete's resistivity by its pore solution resistivity. With the application of formation factor, both the influence of pores and the pore solution within the concrete are well addressed to characterize concrete's pore structure [10, 13]. Since formation factor is a constant value only dependent on the pore structure and interconnectivity, it is recognized as a more effective tool to evaluate the permeability of concrete [13]. Formation factor can be calculated through the equation below:

$$F = \frac{\rho}{\rho_0} = \frac{1}{\varphi \cdot \beta} \quad (1)$$

Where, F is the formation factor; ρ is concrete porosity; ρ_0 is pore solution resistivity; φ is concrete porosity; and β is concrete pore connectivity.

Objective

The objectives of this study were to:

1. Measure the influence of aggregate gradation on concrete's permeability.
2. Optimize concrete mixture designs that meet strength, permeability, and workability criteria for construction.

Scope

To fulfill the objectives of this study, five different aggregate gradation techniques were used to prepare concrete mixtures. Durability tests through surface resistivity and formation factor were conducted to determine the optimal gradation for concrete mixture design.

Methodology

Five different aggregate gradation techniques (Shilstone coarseness factor chart, Power curve, 5-20 band [specified in Louisiana Standard Specifications for Roads and Bridges], Tarantula curve, and a gap gradation [60/40 coarse-to-fine aggregate ratio]) were employed in this study. For each technique, four different gradations were tried to study the packing density based on the aggregate's void contents (per ASTM C29, see Table 1). Generally, the gradations that produced the highest and lowest packing density for each gradation technique were then used to prepare concrete mixtures. However, it should be noted that some gradations were not selected for the final comparative testing due to their very poor workability during the trial mix, though they have the highest or the lowest void ratio. The selected gradations for comparative testing are listed in Table 2. Surface resistivity (AASHTO T 358) and formation factor (AASHTO TP 119-15 Option A and AASHTO PP 84-18) tests were performed for the prepared concrete samples to investigate the influence of different gradations on concrete's permeability.

Table 1. Gradations used for packing density analysis

Gradation technique and designation		Total % passing for each sieve													% Voids
		2''	1.5''	1''	¾''	½''	⅜''	#4	#8	#16	#30	#50	#100	#200	
5-20 Band	5-1	100	100	96	86	74	62	50	38	26	14	4	0.0	0.0	22.6
	5-2	100	100	100	90	64	48	35	28	20	14	0.0	0.0	0.0	24.8
	5-3	100	100	100	90	66	51	35	27	25	19	1	0.0	0.0	24.8
	5-4	100	100	100	92	84	60	35	25	18	12	0.0	0.0	0.0	25.3
Gap Graded	#57	100	100	96	-	25	-	10	0.0	0.0	0.0	0.0	0.0	0.0	22.0
	#67	100	100	100	100	-	25	10	0.0	0.0	0.0	0.0	0.0	0.0	25.7
	#89	-	-	-	-	100	90	25	5	0.0	0.0	0.0	0.0	0.0	25.7
	#467	100	100	-	30	-	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.0
Tarantula	T-1	100	100	94	84	69	54	39	33	27	16	2	0.0	0.0	22.3
	T-2	100	100	84	65	46	27	8	8	8	4	0.0	0.0	0.0	32.4
	T-3	100	100	100	100	96	92	74	62	50	30	10	0.0	0.0	25.6
	T-4	100	100	97	81	66	58	43	35	29	19	3	1	0.0	22.2
Power	P-1	100	100	100	86.9	71.1	61.5	42.8	29.2	19.4	12.2	6.8	2.9	0.0	25.2

Gradation technique and designation		Total % passing for each sieve													% Voids
		2’’	**1.5’’**	**1’’**	**¾’’**	**½’’**	**⅜’’**	**#4**	**#8**	**#16**	**#30**	**#50**	**#100**	**#200**	
	P-2	100	100	100	92	78	56	39	27	19	13	4	1	0.0	26.5
	P-3	100	100	82.2	71.5	58.5	50.6	35.2	24.0	15.9	10.1	5.6	2.4	0.0	24.2
	P-4	100	100	100	90	78	55	40	38	19	5	3	2	0.0	25.4
Shilstone	S-1	100	100	94	84	69	61	46	35	23	11	2	0.0	0.0	23.7
	S-2	100	100	100	80	64	46	34	24	14	7	2	0.0	0.0	26.3
	S-3	100	100	98	90	75	65	51	45	34	22	6	1	0.0	22.4
	S-4	100	100	99	84	69	45	33	32	24	15	5	0.0	0.0	22.2

Table 2. Selected aggregate gradations for concrete mixture design

Gradation technique and designation		Coarse		Fine		Combined		
		SG	**ABS (%)**	**SG**	**ABS (%)**	**Dry UW (pcf)**	**SG**	**% Voids**
5-20 Band	5-1	2.52	2.10	2.60	0.70	123.60	2.56	22.6
	5-3	2.52	2.20	2.61	0.60	119.68	2.55	24.8
Gap Graded	#57	2.51	2.30	2.62	0.40	124.24	2.55	22.0
	#467	2.54	1.60	2.62	0.40	119.52	2.57	26.0
Tarantula	T-3	2.52	2.30	2.61	0.60	120.00	2.59	25.6
	T-4	2.52	2.20	2.61	0.70	124.00	2.56	22.2
Power	P-2	2.52	2.20	2.60	0.70	116.8	2.55	26.5
	P-3	2.53	1.80	2.60	1.00	120.56	2.55	24.2
Shilstone	S-1	2.53	2.00	2.59	1.00	121.52	2.56	23.7
	S-2	2.52	2.00	2.61	0.60	117.12	2.55	26.3
Note: SG – Specific Gravity; ABS – Absorption; UW – Unit Weight.								

Materials

The cementitious materials used in this study included type I portland cement, class C fly ash, and slag cement. Gravel was used as the coarse aggregate in this study, as it is more commonly used in local practice and is also more sensitive to changes in gradation. Taylor et al. found that an acceptable workability could be obtained when the paste volume is at least 1.5 times greater than the volume of voids between the aggregate particles [8]. Therefore, as a comparison to the baseline of 650 pcy, a reduced cement content based on a 1.5 paste-to-voids volume ratio was applied to the second set of mixture designs to investigate the concrete's permeability when the cement content is close to the lower boundary. Table 3 summarizes the concrete mixture design variables for this study.

Table 3. Concrete mixture design variables

Variable	Levels	Description
Aggregate gradation techniques	5 x 2	Shilstone chart; Power curve; 5-20 band; Tarantula curve; gap gradation
w/cm ratio	1	0.45
Coarse aggregate type	1	Gravel
Cementitious material systems	3	100% portland cement; 70% portland cement and 30% class C fly ash; 50% portland cement and 50% slag cement
Cementitious material content	2	650 lbs./yd.^{3} (baseline); and a reduced amount based on a 1.5 paste-to-voids volume ratio
Total mixtures: 60		

Test Methods

For each mixture, nine 4'' x 8'' concrete cylinders were prepared for compressive strength, surface resistivity, and formation factor tests. During the concrete mixing, slump, vibrating Kelly ball penetration, air content, and unit weight were also tested for each mixture. Table 4 summarizes the testing matrix. The following test procedures were followed in testing the concrete properties in this study:

- ASTM C143, Standard Test Method for Slump of Hydraulic-Cement Concrete [14]
- AASHTO TP 129-21, Standard Method of Test for Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete [15]
- ASTM C231, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method [16]
- ASTM C138, Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete [17]
- ASTM C29, Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate [18]
- ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [19]
- AASHTO T 358, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration [20]
- AASHTO TP 119-15, Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test [21]
- TP119-15 (Option A), Immersion of specimens in a calcium hydroxide saturated simulated pore solution
- Simulated pore solution was prepared based on the procedure in ASTM C1876 [22]
- ρ_0=0.0127 kΩ*cm was used as the pore solution resistivity during the calculation of formation factor

Table 4. Experimental testing matrix

Property	Method	No. of Specimens	Age (days)
Slump	ASTM C143	1	-
Vibrating Kelly Ball	AASHTO TP 129-21	1	-
Air Content	ASTM C231	1	-
Unit Weight	ASTM C138	1	-
Bulk Density and Voids in Aggregate	ASTM C29	1	-
Compressive Strength	ASTM C39	3	28
Surface Resistivity (SR)	AASHTO T 358	3	14, 28, 56, 90
Formation Factor	AASHTO TP 119-15 (Option A) AASHTO PP 84-18	3	14, 28, 56, 90

Discussion of Results

Fresh Properties

The fresh properties, including slump, VKelly Index (Kelly Ball testing), air content, and unit weight (UW), are listed in Table 5 and Table 6. It should be noted that Kelly Ball testing was only applied to the mixes with measured slumps less than three inches. Due to the very fast penetration in Kelly Ball testing, there were not enough data points obtained to calculate the VKelly Index for samples C-5049, C-5050, C-5065 and C-5068. In order to facilitate the comparison, Figure 1 presents the slump testing results for all the mixes with 650 pcy cementitious materials. For the gap graded, Tarantula, and Shilstone gradation techniques, the mix with the lower aggregate void ratio generally has a better workability than those with higher aggregate void ratios. However, such a difference is not very significant for the mixes with the 5-20 band and 0.45 Power gradation curves. Instead, 5-20 band gradation 5-3 and Power gradation P-2, though both of them have a higher aggregate void ratio, have a higher slump value than gradation 5-1 and P-3 when using cementitious system 100TI. The slump testing results for the samples with minimum cementitious materials are plotted in Figure 2. When compared with Figure 1, it can be observed that the reduced amount of cementitious materials led to a significant decrease in the slump values for the majority of the mixes.

Table 5. Fresh properties for the samples with 650 pcy cementitious materials

Gradation technique and designation		Cementitious material systems		Sample No.	Slump (inch)	VKelly Index (Kelly Ball)	Air Content (%)	UW (pcf)
		Proportion Design	Total Weight					
5-20 Band	5-1	100TI	650 pcy	C-4959	6.25	-	2	146.16
		70TI/30C		C-4960	7	-	1	147.2
		50TI/50S		C-4962	5.5	-	1.9	146.4
	5-3	100TI	650 pcy	C-4963	7	-	1.1	146.88
		70TI/30C		C-4964	6.75	-	0.9	147.12
		50TI/50S		C-4966	5.75	-	1.1	146.08
Gap Graded	#57	100TI	650 pcy	C-4955	4.5	-	1.7	147.44
		70TI/30C		C-4956	8.25	-	0.7	145.6

Gradation technique and designation		Cementitious material systems		Sample No.	Slump (inch)	VKelly Index (Kelly Ball)	Air Content (%)	UW (pcf)
		Proportion Design	**Total Weight**					
		50TI/50S		C-4958	6	-	1.5	143.68
	#467	100TI	650 pcy	C-5023	1.5	0.425	2.3	145.84
		70TI/30C		C-5024	1	0.495	1.8	148.96
		50TI/50S		C-5025	3.25	-	1.9	146
Tarantula	T-3	100TI	650 pcy	C-4971	0.5	0.598	4.3	143.52
		70TI/30C		C-4972	1.25	1.091	3	144.88
		50TI/50S		C-4974	0.25	0.638	4	143.2
	T-4	100TI	650 pcy	C-4967	3.5	-	1.5	147.76
		70TI/30C		C-4968	6.25	-	0.9	147.92
		50TI/50S		C-4970	4.75	-	1.2	146.16
Power	P-2	100TI	650 pcy	C-4979	2.5	0.814	1.4	145.52
		70TI/30C		C-4980	4.5	-	1.3	146.48
		50TI/50S		C-4982	1	0.945	1.2	147.2
	P-3	100TI	650 pcy	C-4975	1.5	0.623	1.2	148.96
		70TI/30C		C-4976	4.5	-	0.7	148.8
		50TI/50S		C-4978	4.25	-	0.9	148.4
Shilstone	S-1	100TI	650 pcy	C-4983	5.25	-	1.6	147.84
		70TI/30C		C-4984	7.5	-	1	147.12
		50TI/50S		C-4986	7	-	1.4	147.52
	S-2	100TI	650 pcy	C-4987	3.75	-	1.2	147.04
		70TI/30C		C-4988	4	-	1	146.48
		50TI/50S		C-4990	4	-	1.3	146.48

Note: 100TI – 100% portland cement; 70TI/30C – 70% portland cement and 30% class C fly ash; 50TI/50S – 50% portland cement and 50% slag cement.

Table 6. Fresh properties for the samples with minimum cementitious materials

Gradation technique and designation		Cementitious material systems		Sample No.	Slump (inch)	VKelly Index (Kelly Ball)	Air Content (%)	UW (pcf)
		Proportion Design	Total Weight (pcy)					
5-20 Band	5-1	100TI	534	C-5054	0.5	0.615	2.3	146.96
		70TI/30C	368+158	C-5055	2	0.778	1.5	147.12
		50TI/50S	261+261	C-5056	1.25	0.754	2.2	146.88
	5-3	100TI	572	C-5057	1.5	0.648	1.4	147.2
		70TI/30C	394+169	C-5058	0.75	0.777	1	146.08
		50TI/50S	280+280	C-5059	1	0.53	1.2	146.46
Gap Graded	#57	100TI	523	C-5036	0.25	0.341	3.5	146.4
		70TI/30C	361+155	C-5037	0.25	0.357	3.4	146.32
		50TI/50S	256+256	C-5038	0.25	0.351	2.6	145.36
	#467	100TI	591	C-5044	0.5	0.74	2.4	146.8
		70TI/30C	408+175	C-5045	1.5	0.945	1.5	148.08
		50TI/50S	289+289	C-5046	0.5	1.142	2.3	147.44
Tarantula	T-3	100TI	585	C-5051	0	0.179	8.5	136.32
		70TI/30C	403+173	C-5052	0	0.136	6.8	137.84
		50TI/50S	286+286	C-5053	0	0.181	9.5	135.2
	T-4	100TI	526	C-5048	0.25	0.802	2.2	147.44
		70TI/30C	363+156	C-5049	0.5	Penetration Too fast	1.2	149.12
		50TI/50S	257+257	C-5050	0.25	Penetration Too fast	2.3	146.56
Power	P-2	100TI	599	C-5063	1	0.397	1.5	146
		70TI/30C	413+177	C-5064	0.25	0.701	1.2	145.12
		50TI/50S	293+293	C-5065	0.25	Penetration Too fast	1.5	146.32
	P-3	100TI	562	C-5060	0.5	0.364	1.4	148.24
		70TI/30C	387+166	C-5061	0.75	0.363	1	145.6
		50TI/50S	275+275	C-5062	0.25	0.398	1	148

Gradation technique and designation		Cementitious material systems		Sample No.	Slump (inch)	VKelly Index (Kelly Ball)	Air Content (%)	UW (pcf)
		Proportion Design	Total Weight (pcy)					
Shilstone	S-1	100TI	553	C-5066	0.25	0.806	1.9	148.24
		70TI/30C	381+163	C-5067	2.5	1.127	1.6	146.8
		50TI/50S	271+271	C-5068	1	Penetration Too fast	1.7	148.4
	S-2	100TI	596	C-5069	0.25	0.355	1.3	147.44
		70TI/30C	411+176	C-5070	0.5	0.432	1.2	146.08
		50TI/50S	291+291	C-5071	0.5	0.4	1.4	148.16

Note: 100TI – 100% portland cement; 70TI/30C – 70% portland cement and 30% class C fly ash; 50TI/50S – 50% portland cement and 50% slag cement.

Figure 1. Slump testing results with 650 pcy cementitious materials

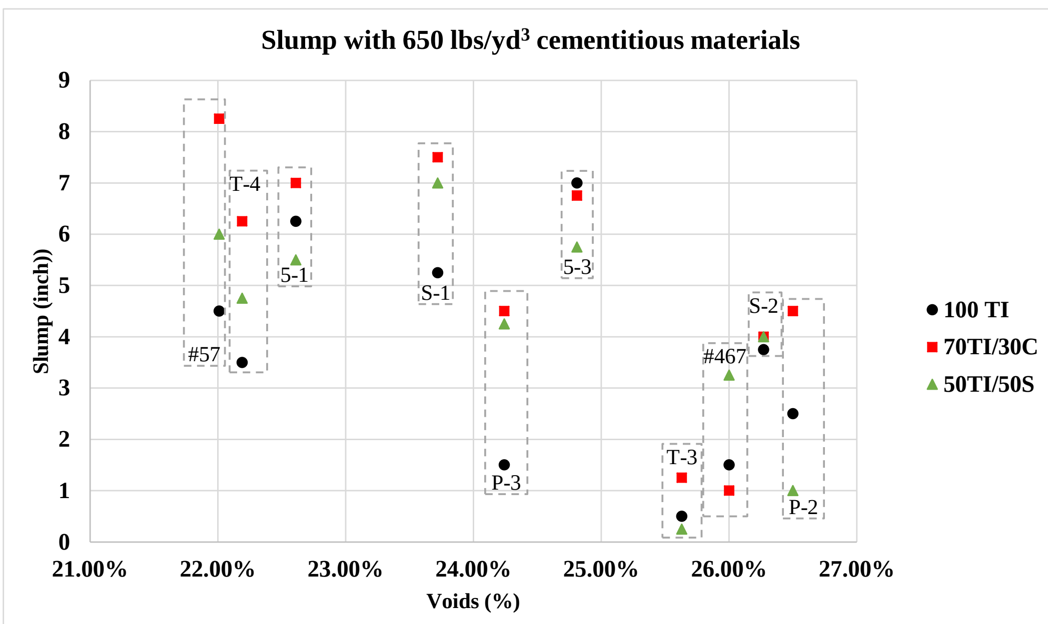
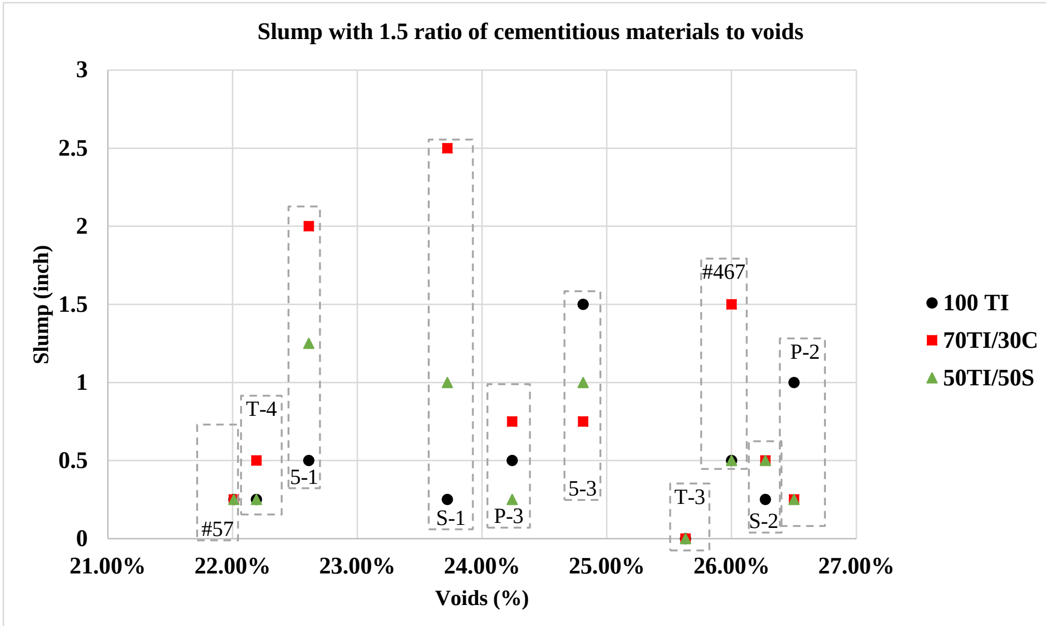


Figure 2. Slump testing results with minimum cementitious materials



Compressive Strength

Figure 3 shows the compressive strength testing results for the samples with 650 pcy cementitious materials. The results show that the cementitious system 70TI/30C produced the highest compressive strength for most of the gradation curves, with the exception of the 0.45 power curve P-2, which has the highest aggregate void ratio in this study. The cementitious system 50TI/50S produced the lowest compressive strength, except for the gap graded gradation #57 and Shilstone gradation S-1. By comparing the results between the different gradation curves for each gradation technique, it is found that:

- For gap graded curves, gradation #57, which has a lower aggregate void ratio, produced a higher compressive strength when using the cementitious systems 70TI/30C and 50TI/50S.
- For Tarantula curves, gradation T-4, which has a lower aggregate void ratio, produced a higher compressive strength for all three cementitious systems.
- For 5-20 band curves, gradation 5-1, which has a lower aggregate void ratio, produced a higher compressive strength when using the cementitious system 70TI/30C.
- For Shilstone curves, gradation S-1, which has a lower void ratio, produced a higher compressive strength when using the cementitious systems 70TI/30C and 50TI/50S.

- For 0.45 Power curves, gradation P-3, which has a lower void ratio, produced a higher compressive strength than P-2 only when using the cementitious system 70TI/30C, which is similar to the 5-20 band curves.

Figure 3. Compressive strength testing results with 650 pcy cementitious materials

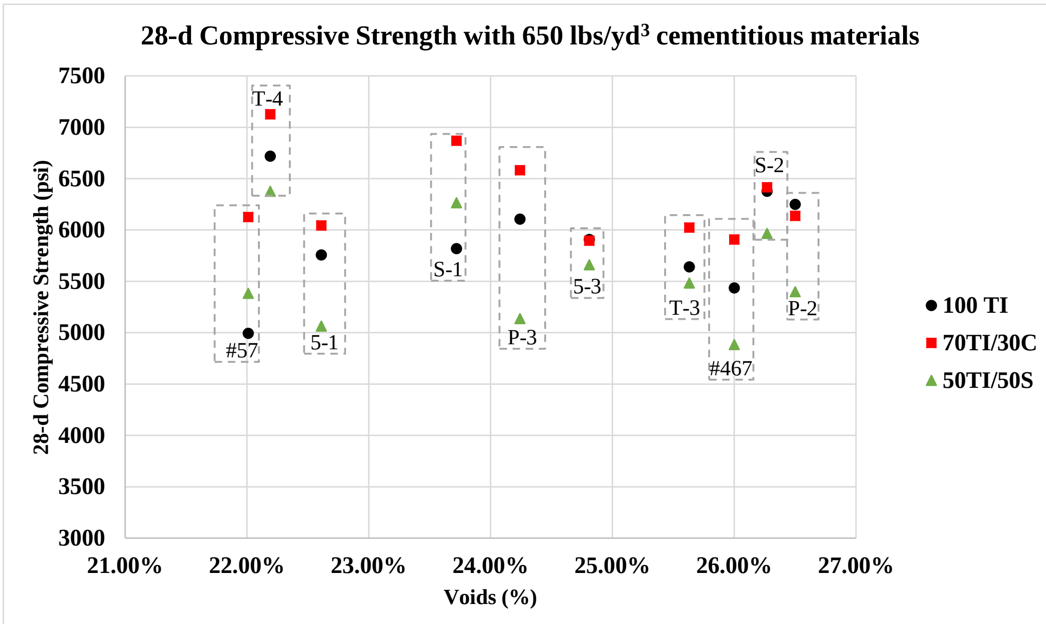
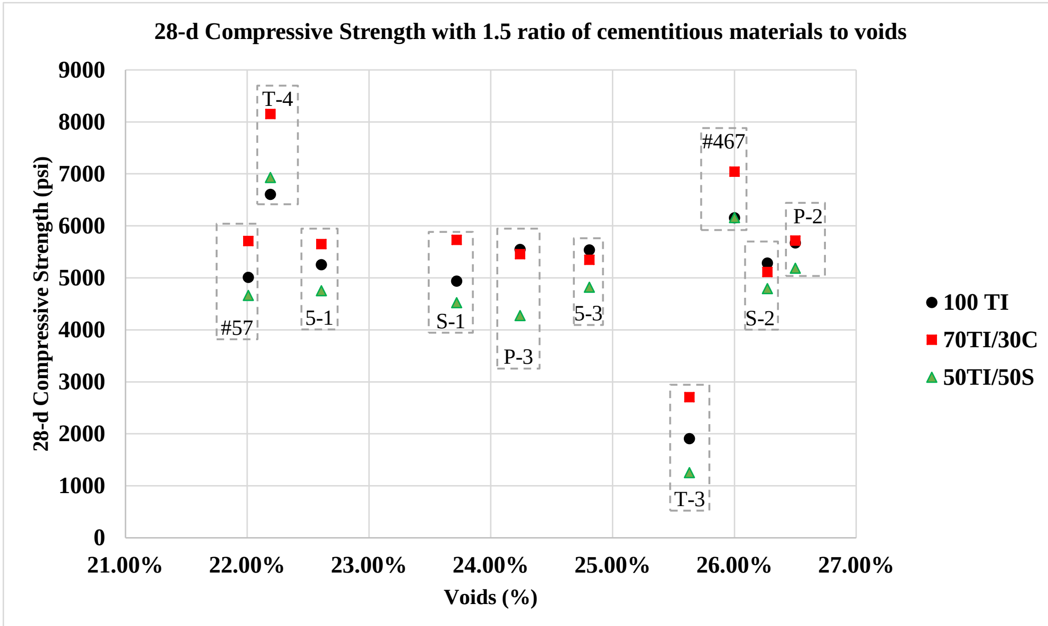


Figure 4 presents the compressive strength testing results for the samples with minimum cementitious materials. It can be observed that the cementitious system 70TI/30C produced the highest compressive strength for the majority of the gradation curves, and the cementitious system 50TI/50S produced the lowest compressive strength for most of the gradation curves. It is also found that the 5-20 band, Shilstone, and 0.45 Power curves have been characterized with a more consistent compressive strength (i.e., in the range of 4,000 – 6,000 psi) for the samples with a lower aggregate void ratio when compared to the samples with a higher aggregate void ratio. It should be noted that there is a significant difference between the compressive strength testing results for the two Tarantula gradations with the minimum amount of cementitious materials.

Figure 4. Compressive strength testing results with minimum cementitious materials

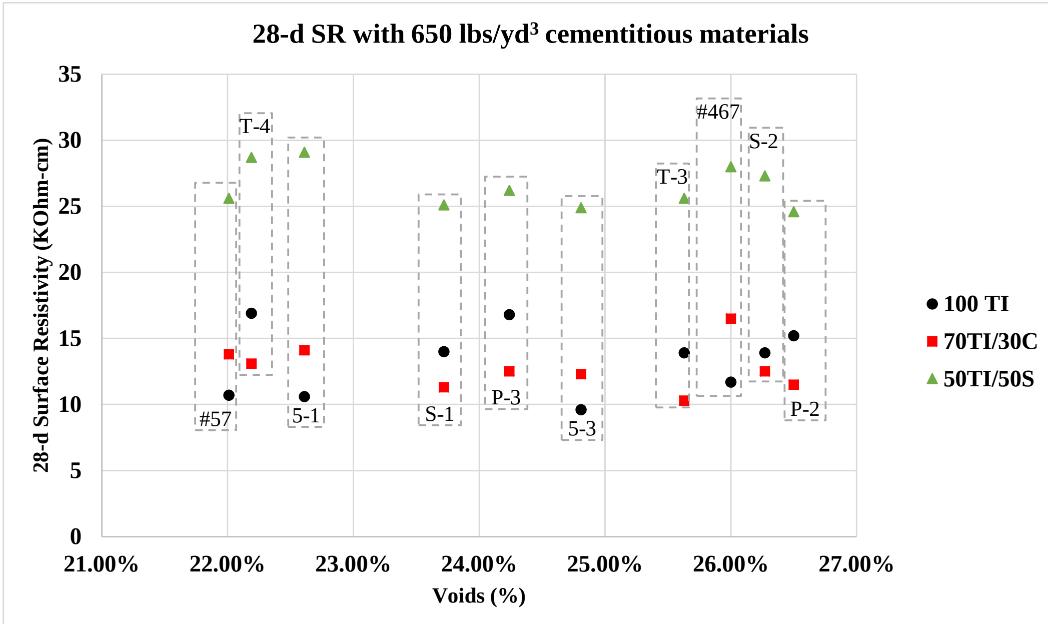


28-d Surface Resistivity and Formation Factor

The 28-d surface resistivity (SR) testing results for the specimens with 650 pcy cementitious material are shown in Figure 5. It is revealed that the cementitious system 50TI/50S produced the highest surface resistivity for all the samples after 28 days of curing. Specifically:

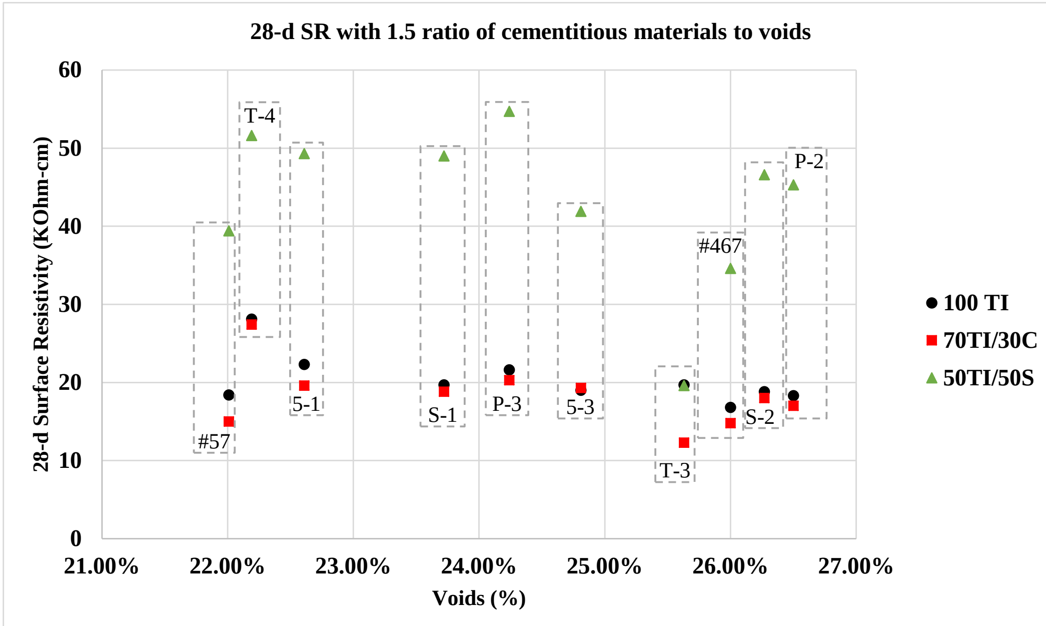
- For the gap graded curves, gradation #57, which has a lower aggregate void ratio, produced a lower surface resistivity for all three cementitious systems.
- For the Tarantula, 5-20 band, and 0.45 Power curves, the gradations with a lower aggregate void ratio produced a higher surface resistivity for all three cementitious systems.
- For the Shilstone curves, gradation S-1, which has a lower aggregate void ratio, produced a higher surface resistivity when using cementitious systems 70TI/30C and 50TI/50S, while the opposite is true for cementitious system 100TI.

Figure 5. Surface resistivity testing results with 650 pcy cementitious materials



From Figure 6, it can be observed that the cementitious system 50TI/50S also produced the highest surface resistivity for all of the samples after 28 days of curing when using the minimum cementitious materials, while the cementitious system 70TI/30C produced the lowest surface resistivity, except for gradation 5-3. For the five different gradation techniques, all of the gradation curves with a lower void ratio produced a higher surface resistivity for all three cementitious systems, though the difference in values is small for some gradations.

Figure 6. Surface resistivity testing results with minimum cementitious materials



The formation factor testing results for 28 days of curing are presented in Figure 7 and Figure 8. Generally, the mixtures prepared with the minimum cementitious materials produced a higher formation factor than those with 650 pcy cementitious materials, except for the gradation T-3, which could be due to the bad specimen quality caused by the very poor workability (i.e., slump value of zero). A comparison between the specimens with different cementitious systems reveals that cementitious system 50TI/50S produced the highest formation factor for all of the gradation curves except T-3, which has a slump value of zero.

For the mixtures prepared with 650 pcy cementitious materials (see Figure 7):

- For the two gap graded curves, gradation #57, which has a lower aggregate void ratio, produced a lower formation factor for all three cementitious systems.
- For the two Tarantula curves and the two 5-20 band curves, the gradation with a lower aggregate void ratio produced a higher surface resistivity for all three cementitious systems.
- For the two 0.45 Power curves, gradation P-3, which has a lower aggregate void ratio, produced a higher formation factor when using cementitious systems 100TI and 70TI/30C, while the opposite is true for cementitious system 50TI/50S.

- For the two Shilstone curves, gradation S-1, which has a lower aggregate void ratio, only produced a slightly higher formation factor when using cementitious system 100TI.

For the samples prepared with the minimum cementitious materials (see Figure 8), it is found that the gradation curves with a lower aggregate void ratio generally produced a higher formation factor for all three cementitious systems, except for the gap graded curve when using cementitious system 70TI/30C.

Figure 7. Formation factor testing results with 650 pcy cementitious materials

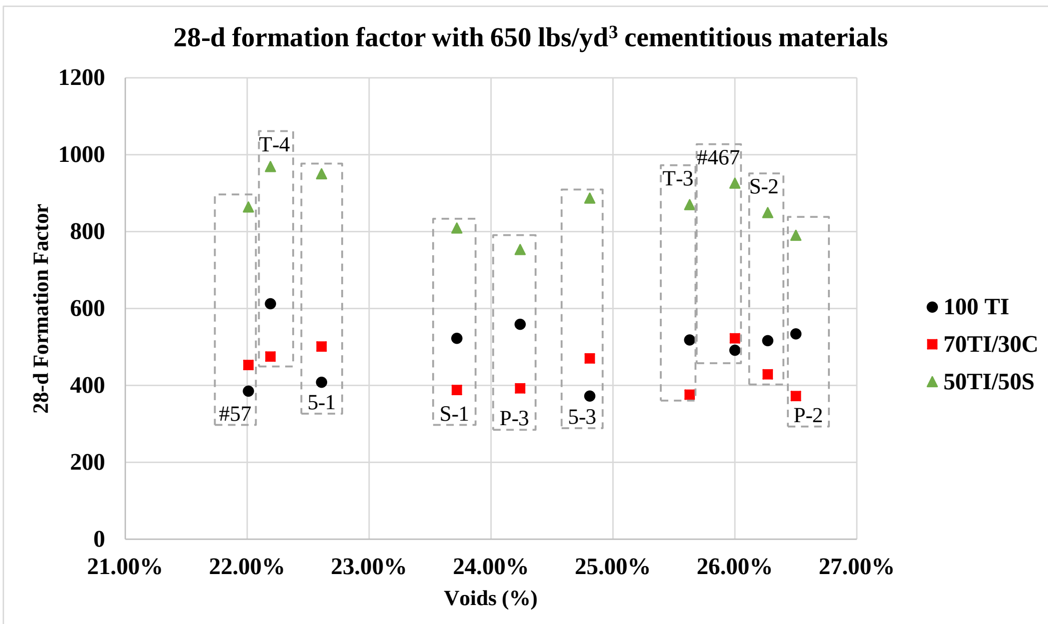
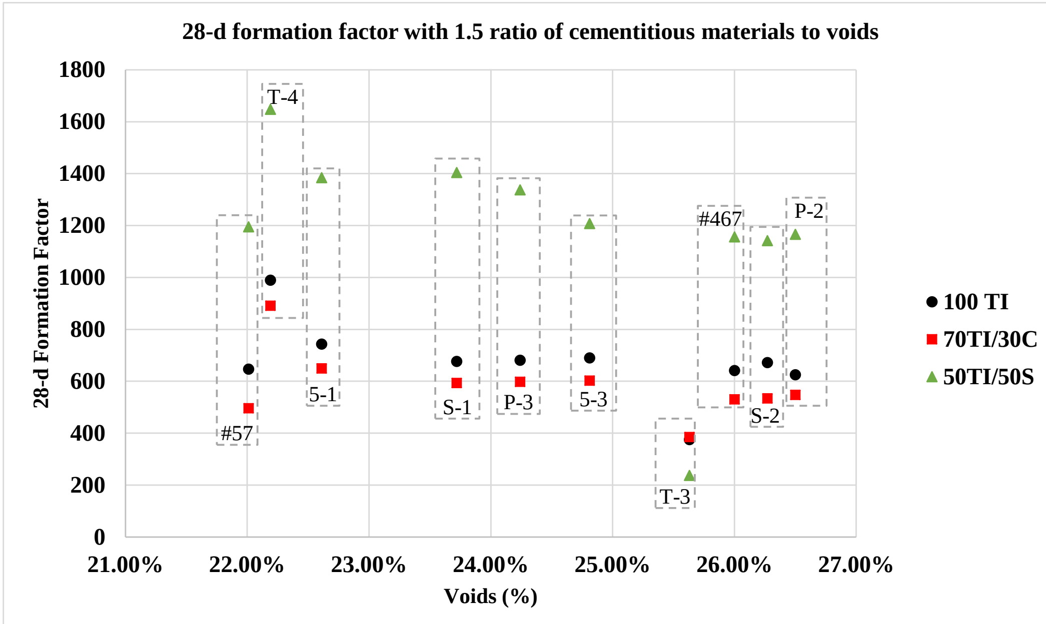


Figure 8. Formation factor testing results with minimum cementitious materials



Surface Resistivity and Formation Factor Development over Time

Figure 9 to Figure 12 present the development of surface resistivity and formation factor over time for specimens with 650 pcy and the minimum amount of cementitious materials. From Figure 9, which shows the development of surface resistivity for specimens with 650 pcy cementitious materials, it can be observed:

- For cementitious system 100TI, the surface resistivity increased over time for gradations #57, 5-1, 5-3, and P-2. For gradations P-3, #467, and S-2, the surface resistivity decreased after 56 days of curing. For gradation S-1, the surface resistivity stopped growing at 56 days. For gradations T-4 and T-3, the surface resistivity decreased after 28 days.
- For cementitious system 70TI/30C, the surface resistivity increased over time for most of the gradations, with the exception of the gap graded gradation #467, for which the surface resistivity decreased after 56 days of curing.
- Among all three cementitious systems, 50TI/50S produced the highest surface resistivity for all of the gradations at all four different curing times (i.e., 14 days, 28 days, 56 days, and 90 days). Similar to cementitious system 70TI/30C, the surface resistivity also increased over time for most of the gradations with the cementitious

system 50TI/50S, except the gap graded #467, for which the surface resistivity decreased after 56 days of curing.

Figure 10 presents the development of formation factor for specimens with 650 lbs./yd.^{3} cementitious materials. It is found that:

- For cementitious system 100TI, the formation factor increased over time for the majority of the gradations, except the 5-20 band gradation 5-3 and gap graded gradation #467, for which the formation factor decreased after 56 days of curing.
- For cementitious system 70TI/30C, the formation factor increased over time for the majority of the gradations, with the exception of the gap graded gradation #467, for which the formation factor decreased after 56 days of curing.
- Among all three cementitious systems, 50TI/50S produced the highest formation factor at all four different curing times (i.e., 14 days, 28 days, 56 days, and 90 days). Similar to the cementitious system 70TI/30C, the formation factor also increased over time for the majority of the gradations with cementitious system 50TI/50S, with the exception of the gap graded #467, for which the formation factor decreased after 56 days of curing.

The development of surface resistivity for specimens prepared with minimum cementitious materials is shown in Figure 11. It is found that:

- For cementitious system 100TI, the surface resistivity increased over time for gradations #57, T-4, 5-3, P-3, T-3, S-2, and P-2. For 5-1, surface resistivity started to decrease after 28 days. For gradations S-1 and #467, the surface resistivity decreased after 56 days of curing.
- For cementitious system 70TI/30C, the surface resistivity increased over time for the majority of the gradations, with the exception of the gap graded gradation #467, for which the surface resistivity slightly decreased after 56 days of curing.
- Among all three cementitious systems, 50TI/50S produced the highest surface resistivity for all the gradations, except T-3 at 14 days and 28 days, at all four different curing times (i.e., 14 days, 28 days, 56 days, and 90 days). Similar to the cementitious system 70TI/30C, the surface resistivity also increased over time for most of the gradations with the cementitious system 50TI/50S, with the exception of the gap graded #467, for which the surface resistivity decreased after 56 days of curing.

From Figure 12, which shows the development of formation factor for specimens with minimum cementitious materials, it can be observed that:

- For cementitious system 100TI, the formation factor increased over time only for gradations #57 and #467 while all other gradations showed that the formation factor decreased after 56 days of curing.
- For cementitious system 70TI/30C, the formation factor increased over time for all gradations, though it almost stopped increasing for 5-1 at 56 days.
- Among all three cementitious systems, 50TI/50S produced the highest formation factor for all gradations (except T-3 at 14 days, 28 days, 56 days and 90 days) at all four different curing times (i.e., 14 days, 28 days, 56 days, and 90 days). For cementitious system 50TI/50S, the formation factor increased over time for the majority of the gradations, except the gradation 5-20 band 5-1 and Shilstone S-2, for which the formation factor decreased after 56 days of curing.

A comparison between the surface resistivity testing results (see Figure 9 and Figure 11) shows that:

- For 100 TI, reducing the amount of cementitious materials helped increase the surface resistivity for all gradations.
- For 70TI/30C, reducing the amount of cementitious materials helped increase the surface resistivity for all gradations except #467. It is also noted the increase was more than 95% for gradation T-4.
- For 50TI/50S, the surface resistivity was increased significantly by reducing the amount of cementitious materials for most of the gradations. However, the surface resistivity decreased for gradation T-3.

By comparing the formation factor testing results (see Figure 10 and Figure 12), it is found that:

- For 100 TI, reducing the amount of cementitious materials helped increase the formation factor for most of the gradations, except T-3 and P-2.
- For 70TI/30C, reducing the amount of cementitious materials helped increase the formation factor for all the gradations except T-3. It is also noted that the increase was more than 95% for gradation T-4.

- For 50TI/50S, the formation factor was increased significantly (i.e., >40%) by reducing the amount of cementitious materials for most of the gradations, with the exception of 5-1, for which the increase was minimal. The formation factor decreased significantly for gradation T-3.

Figure 9. Development of surface resistivity for samples with 650 pcy cementitious materials

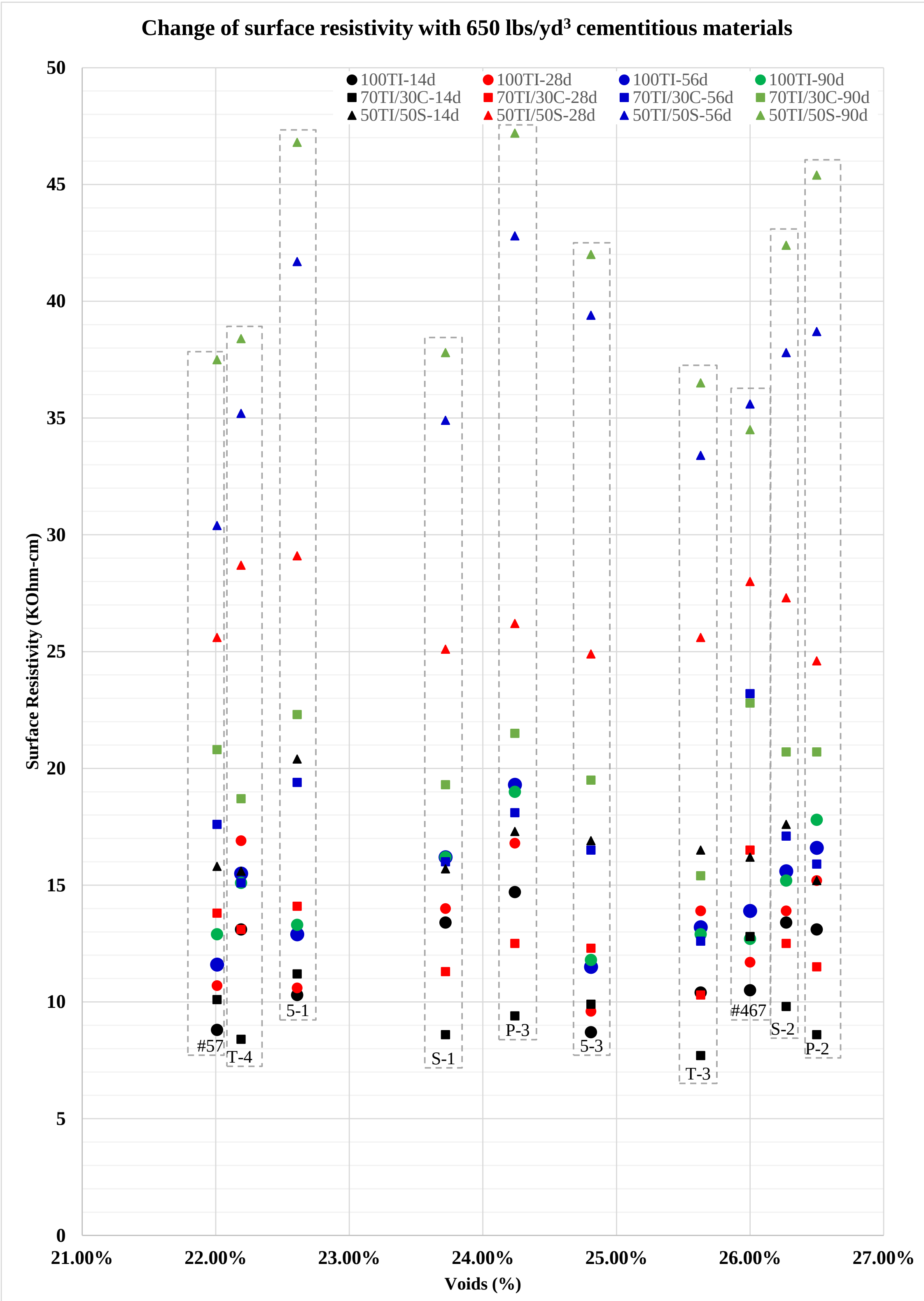


Figure 10. Development of formation factor for samples with 650 pcy cementitious materials

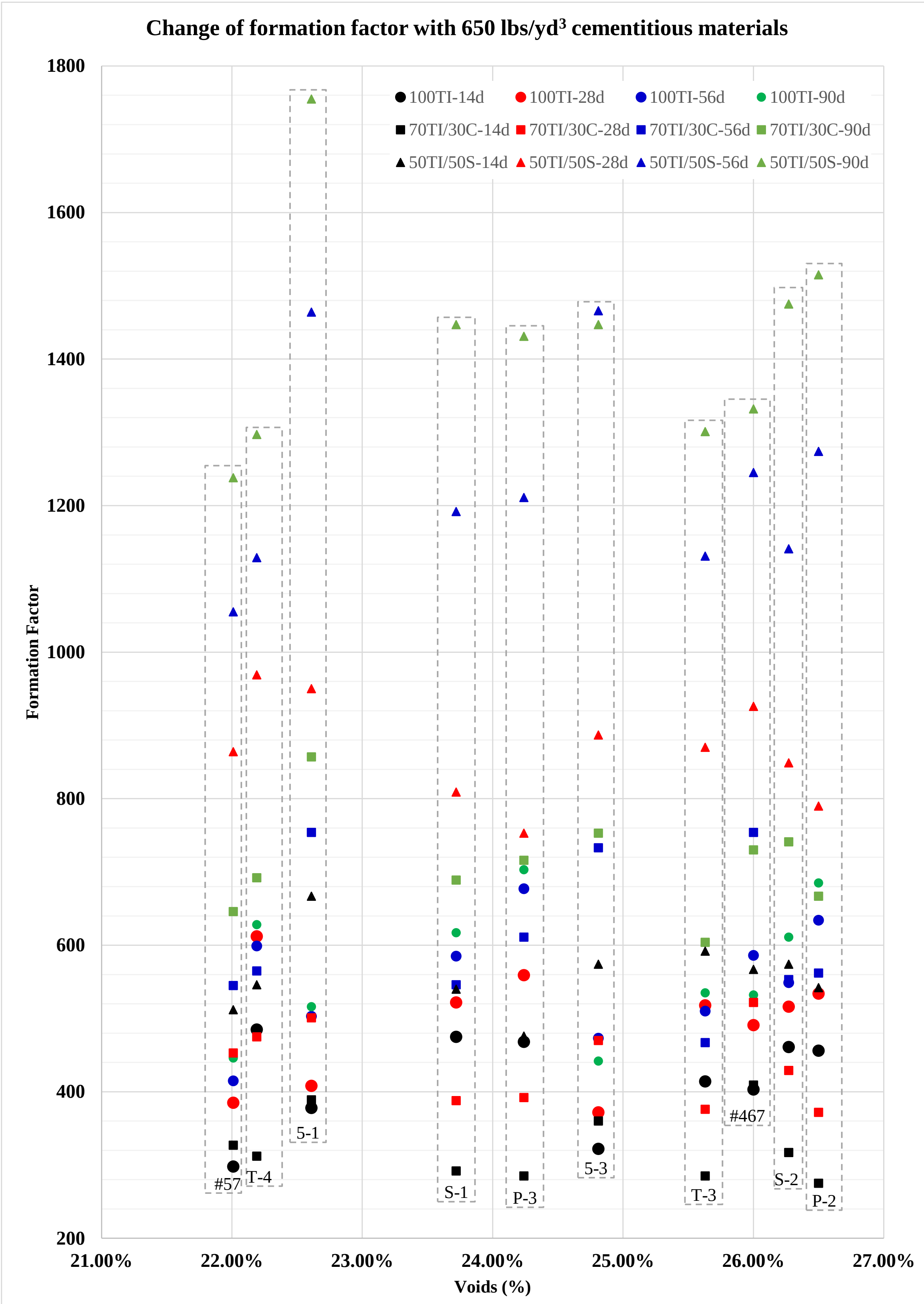


Figure 11. Development of surface resistivity for samples with minimum cementitious materials

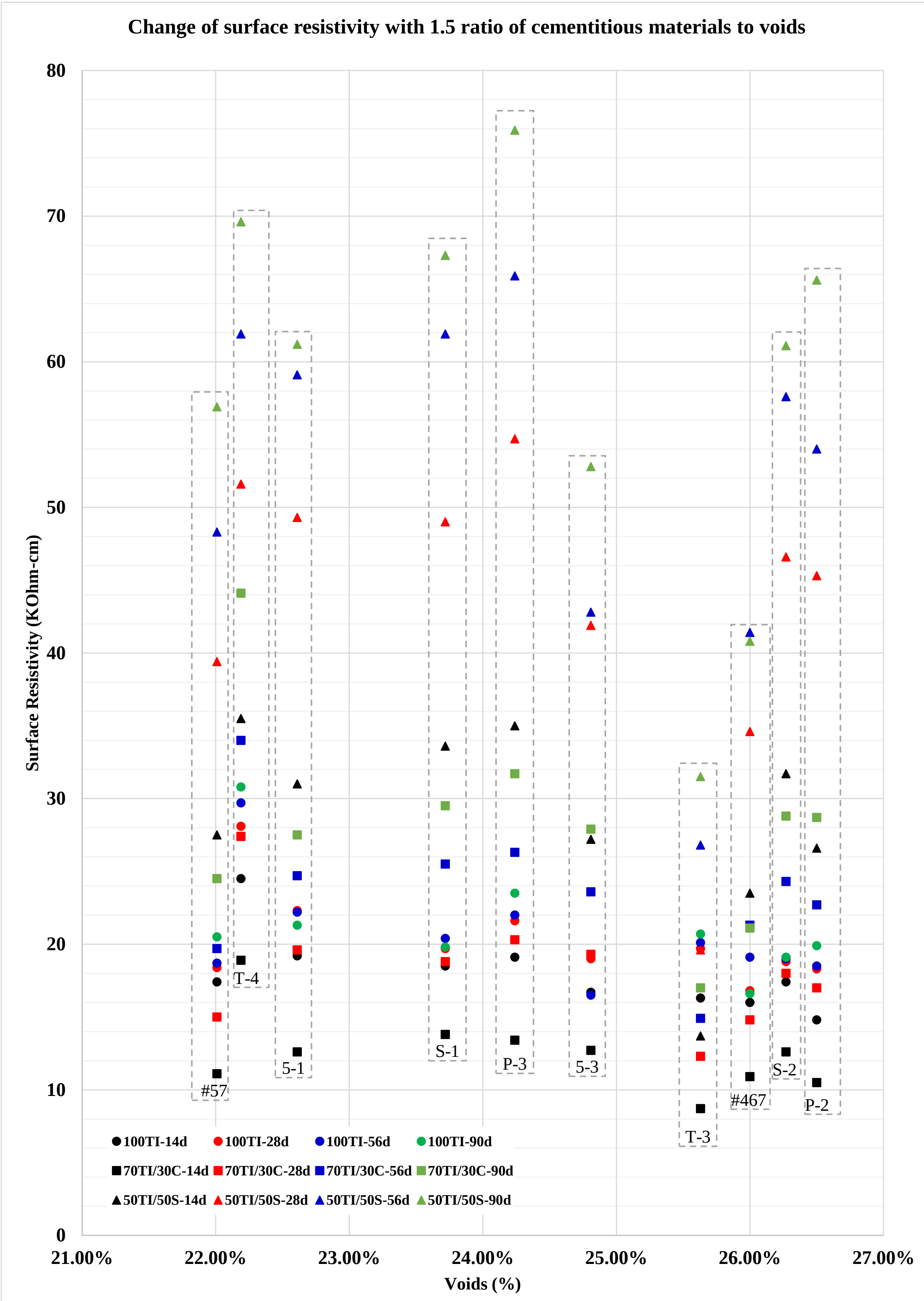
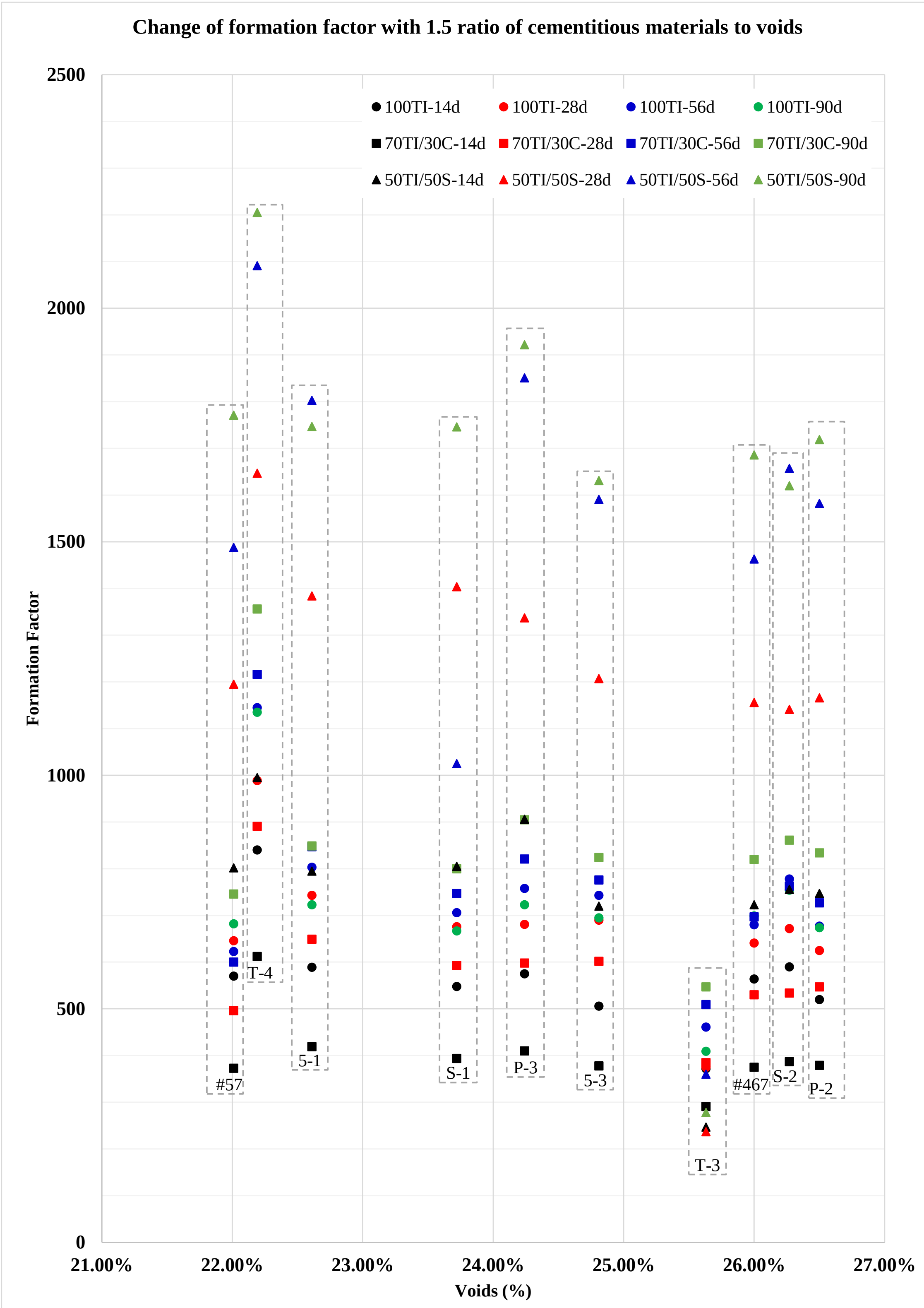


Figure 12. Development of formation factor for samples with minimum cementitious materials



Conclusions

In this study, five different aggregate gradation techniques were used to prepare concrete mixtures. Through a comparison of the test results, it is found that for gravel aggregates:

- Tarantula gradation T-4 with cementitious system 50TI/50S and the minimum amount of cementitious materials produced the highest formation factor (i.e., more than 2,000 after 56-day curing) and the second highest surface resistivity among all 20 mixtures.
- Power gradation P-3 with cementitious system 50TI/50S and the minimum amount of cementitious materials produced the second highest formation factor (i.e., more than 1,800 after 56-day curing) and the highest surface resistivity among all 20 mixtures.
- Tarantula gradation T-3 with the minimum amount of cementitious materials produced a slump value of zero, a very low 28-d compressive strength (i.e., less than 3,000 psi), and a very low formation factor for all three cementitious systems.
- Among all three cementitious systems, 50TI/50S produced the highest the surface resistivity and formation factor for the majority of the gradations at all four different curing times (i.e., 14 days, 28 days, 56 days, and 90 days).

Based on the findings, it can be concluded that Tarantula gradation T-4 and Power gradation P-3 would be good gradations for high durability concrete mix design when produced with cementitious system 50TI/50S and the minimum amount of cementitious materials.

Recommendations

To improve concrete's durability, it is recommended to:

- Use the Tarantula or Power gradation technique to select the aggregate with the lowest aggregate void ratio during concrete mix design.
- Use cementitious system 50TI/50S.
- Minimize the amount of cementitious materials, if possible.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
ft.	foot (feet)
in.	inch(es)
lb.	pound(s)
LTRC	Louisiana Transportation Research Center
pcf	pounds per cubic foot
pcy	pounds per cubic yard
psi	pounds per square inch
yd.	yard(s)

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