Impact of Aggregate Gradation on Properties of Portland Cement Concrete

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16. Abstract

Increasingly, aggregates in South Carolina are failing to meet the standard requirements for gradation for use in portland cement concrete. The effect of such failed aggregate gradations on concrete properties and the consequent effect on short- and long-term performance of the structures are poorly understood. Furthermore, a rational basis to accept or reject concrete containing such out-of-specification aggregate is not available at the present time. The goal of this project was to provide SCDOT with guidance on determining whether concrete containing aggregate with an out-of-specification gradation should be accepted or rejected. The principal objective of this investigation was to study the influence of variations in aggregate gradations on selected properties of concrete. The experimental methodology for this research study consisted of using aggregates size fractions that are sieved into individual size fractions and recombining them in definite proportions to create a range of gradations, some within the bounds of the acceptable gradation (Control-1, Control-2, Control-3) and some out-of-specification gradations. Concrete specimens were prepared with such aggregate gradations and a range of fresh and hardened properties of concrete were evaluated. Results from these studies indicated that deviations in fine aggregate gradation from the Control-2 gradation had relatively larger influence on properties of concrete compared to coarse aggregate. Also, the differences in gradations of aggregates within control gradations (i.e. between Control-1 and Control-3 gradation) had more significant influence on properties of concrete, compared to the out-of-specification gradations. In general, the effects of deviations in gradations from the Control-2 gradation had minimal influence on compressive strength and modulus of elasticity of concrete. However, properties such as slump of fresh concrete, split tensile strength and rapid chloride ion permeability were more significantly influenced by the deviations in the gradations.

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ABSTRACT

Aggregates make up a significant volume fraction of concrete and play a major role in determining the fresh and hardened properties of concrete. One of the important aggregate properties that influence the concrete behavior is the aggregate gradation. Increasingly, aggregates in South Carolina are failing to meet the standard requirements for gradation for use in portland cement concrete. The effect of such failed aggregate gradations on concrete properties and the consequent effect on short- and long-term performance of the structures are poorly understood. Furthermore, a rational basis to accept or reject concrete containing such out-of-specification aggregate is not available at the present time.

The goal of this project was to provide SCDOT with guidance on determining whether concrete containing aggregate with an out-of-specification gradation should be accepted or rejected. The principal objective of this investigation was to study the influence of variations in aggregate gradations on selected properties of concrete. The experimental methodology for this research study consisted of selecting two coarse aggregates and two fine aggregates that have had a history of not meeting the standard gradation requirements. Each of these aggregates was sieved into individual size fractions and then recombined in definite proportions to create a predetermined gradation. The gradation of each of the aggregates was systematically varied from the standard requirements to out-of-specification gradation in incremental steps on selected sieve sizes.

In typical standard aggregate gradation specifications, the acceptable cumulative percent passing on any intermediate sieve sizes is not defined by one single limit, rather a range of acceptable percent passing. Therefore, selecting a single gradation within the acceptable limit to serve as a control gradation would be inappropriate. In this study, a series of three control aggregate gradations were created for each of the coarse and fine aggregates studied. These gradations were identified as Control-1, Control-2, and Control-3 gradations. Control-1 and Control-3 gradations represented those distributions that barely met the specification requirements at the acceptable limits of cumulative percent passing. Control-2 gradation represented a distribution for which the cumulative percent passing through each sieve was at exactly the mid-point within the acceptable range. Compared to Control-2 gradation, Control-1 gradation was dominated by coarser fractions, while Control-3 gradation was dominated by finer fractions. In addition to the control gradations, four other aggregate gradations were engineered

such that they failed the acceptable range of gradations on selected sieves by a margin of ± 6% and ± 12% from the allowable cumulative percent passing. These gradation failures were considered as either negative failure (NEG) or positive failure (POS), depending on whether the gradation was outside of Control-1 gradation or Control-3 gradation, respectively.

In concrete mixtures where coarse aggregate gradations were varied, a fine aggregate meeting the Control-2 gradation was used, and in concrete mixtures where fine aggregate gradations were varied, a coarse aggregate meeting the Control-2 gradation was used. All concrete mixtures were proportioned with a fixed quantity of total aggregate content (69% of the volume of concrete, and a coarse/fine aggregate ratio of 1.54 by mass) and a constant water-to-cement ratio of 0.50. No chemical admixtures were used in this investigation in order to avoid their influence on the properties of concrete. As a consequence, the concrete mixtures proportioned in this investigation have somewhat higher w/c ratio and do not necessarily represent typical bridge deck concrete mixtures. Therefore the results from this investigation should only be used as a qualitative indictor of the impact on the aggregate gradation on the properties of concrete. No quantitative limits on acceptable gradation limits should be derived from these findings.

Tests on fresh and hardened concrete were conducted on a series of 7 different mixtures (3 Control gradations and 4 failed gradations) for each aggregate evaluated in this study in an attempt to develop an understanding of the impact of failed aggregate gradations on properties of concrete.

Results from these studies indicated that deviations in fine aggregate gradation from the Control-2 gradation had relatively larger influence on properties of concrete compared to coarse aggregate. The properties most influenced by the changes in fine aggregate gradation included fresh air content, slump, split tensile strength, rapid chloride ion permeability and water absorption of concrete. For instance, with FA-1 fine aggregate, the slump of concrete varied from about 2 inches to 8.75 inches in the range of gradations investigated, with the Control-2 gradation concrete producing a slump of 4.75 inches. Higher slumps were observed in concrete with coarser gradation of fine aggregate and lower slumps were observed in concrete with finer gradations of fine aggregate. However, much of the variation in the slump of concrete occurred due to variation in the gradation of fine aggregate within the limits of acceptable gradation, i.e. between Control-1 and Control-3 gradations. Very little additional change in slump of concrete was observed when the aggregate gradation deviated out of specification, i.e. beyond Control-1 or Control-3 gradations.

The 28-day split tensile strength of concrete decreased with increasing deviation in gradation from Control-2 gradation. However, much of the decrease in the split tensile strength was observed due to changes in gradation within the acceptable limits, i.e. from Control-2 to Control-1 and Control-3 gradations. Further reduction in split tensile strength of concrete was observed beyond Control-1 and Control-3 gradations, however, the reduction was smaller in comparison to the reduction that occurred within the gradation limits. Unlike slump, the split tensile strength decreased as aggregate gradation deviated from Control-2 gradation, on both POS and NEG failed aggregate gradations.

The results from these studies indicate that the 56-day rapid chloride ion permeability (RCP) value of concrete with Control-2 gradation was the lowest. With progressive deviation in aggregate gradation from Control-2 gradations to the boundaries of acceptable limits, the RCP values increased significantly. The RCP values of concrete with failed gradations were in most cases higher than that of Control-1 or Control-3 gradations; however, in view of the fact that RCP values of Control-1 and Control-3 gradations were well beyond what is considered acceptable, concretes produced with failed aggregate gradations would certainly be harmful from a durability perspective. The principal reason for the influence of aggregate gradation on RCP values of concrete can perhaps only be attributed to the nature of the interfacial transition zone (ITZ) in the cement paste surrounding the poorly graded aggregate particles. In this regard, the results from tests on water absorption of concrete support this hypothesis. It should also be noted that the concrete mixtures employed in this investigation were dissimilar to that of a typical bridge deck concrete in the following ways: (i) the w/c ratio of 0.50 is higher than typically what is employed, (ii) the concrete mixtures in this investigation did not contain supplementary cementing materials (SCMs), and (iii) no chemical admixtures were used in this investigation. It is well known that the negative effects of ITZ are often overcome by using suitable SCMs and low w/c ratio along with chemical admixtures. Since the use of SCMs, chemical admixtures and low w/cm ratio are inevitable practices in the field it is unlikely that the deviation of aggregate gradation from standard gradation, within the range investigated in this study will significantly undermine the durability of concrete.

The trends in the fresh air content and water absorption of concrete with changes in the aggregate gradation, were similar to that observed in the RCP values of concrete. Other properties of concrete such as compressive strength, modulus of elasticity were not influenced by changes in aggregate gradation of either fine or coarse aggregates across the entire spectrum of gradations investigated. Drying shrinkage of concrete did not show any definitive trend with changes in the aggregate gradation.

Considering that the standard aggregate gradation is represented by a range of acceptable cumulative percent passing on individual sizes, a diverse array of acceptable aggregate gradations can be generated that still comply with the standard requirements. The results from this study conclusively show that even when the aggregate gradations are within the specified requirements, concretes produced with such diverse aggregate gradations can have a wide range of properties. In particular, variations in fine aggregate gradations appear to have more significant influence compared to coarse aggregate gradations. The properties of concrete that are most influenced by aggregate gradations include fresh concrete properties such as slump and air content, and hardened concrete properties such as split tensile strength, rapid chloride ion permeability and water absorption. Deviation in aggregate gradation beyond the acceptable limits of gradation by a margin of ± 12% cumulative percent passing on specific sieves, appears to influence the concrete properties; however, compared to the range of properties that are encountered when using aggregate that meet the specification requirements, the change in the magnitude of properties of concrete with gradations that are beyond the specification requirements does not appear to be significant.

Based on the findings from this study, it is recommended that as long as plastic properties of concrete such as slump and air content of concrete are within acceptable limits and the concrete is of adequate quality to achieve proper consolidation and finishing characteristics, aggregates that fail to meet the standard requirements by a margin of ± 12% of the acceptable cumulative percent passing on specific sieves may still be used to produced concrete that has a comparable performance to that of an aggregate meeting the standard requirements. However, considering that the properties of concrete affected by aggregate gradation are also properties that affect cracking and durability in concrete, it is important to consider the consequences of deviation in aggregate gradation on selected properties of concrete. In particular, the rapid chloride permeability of concrete is important in the context of the bridge deck. This property can be easily addressed by changing the composition of the cementitious materials, such as adding silica fume, without being influenced by the aggregate gradation. Similarly, a lower w/cm ratio and the use of a high-range water reducer can address the negative impact of the deviations in the aggregate gradations.

The findings from this research are limited by the materials employed in this study and the concrete mixture proportions selected. It is recommended that in future a more comprehensive study involving manufactured sands, supplementary cementing materials and lower w/c ratio than that was employed in this study should be considered.

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1.0 INTRODUCTION

1.1 Background

Aggregate occupies 70% to 75% of the volume of conventional normal strength portland cement concrete and therefore the properties of aggregates have a dominant effect on the overall performance of concrete in its fresh and hardened state. Among the various characteristics of aggregates that have a significant influence on properties of concrete, the size distribution of aggregate particles or otherwise known as *aggregate gradation* plays an important role in achieving the desired properties of concrete [1-5].

Aggregate gradation determines the void content within the structure of aggregate and consequently the amount of cement paste that is required to fill the void space between the aggregate and ensure a workable concrete [5]. As portland cement is the most expensive and high carbon footprint ingredient in concrete, it is desirable to optimize the aggregate gradation to minimize the void content in the aggregate and therefore the volume of cement paste required to achieve a workable, economical and an environmentally sound concrete for a given application. The need to optimize aggregate gradation also arises from the desire to improve rheological, mechanical and durability properties of concrete [6].

Proper aggregate gradation is not only important to ensure a workable concrete mixture that can be compacted easily, but also to minimize problems associated with plastic concrete such as potential for segregation, bleeding and loss of entrained air and potential for plastic shrinkage cracking [3, 4, 7] . Furthermore, most concrete that is used in construction of transportation infrastructure is often vibrated to achieve good compaction in concrete. Concrete containing aggregate with poor gradation can be particularly vulnerable to problems such as segregation in plastic state under vibration.

Cement paste, which fills the void space between the aggregate, has a tendency to shrink when there is a progressive loss of moisture from concrete, either due to evaporation from surface of concrete or through internal consumption of moisture due to hydration reactions of cement. Aggregates in concrete, being generally much stiffer than the hardened cement paste, act to resist the shrinkage behavior of concrete. Aggregate gradation, which determines the relative proportions of aggregate and cement paste in a concrete, therefore dictates the shrinkage behavior of concrete and hence long-term durability of concrete [8]. Aggregate is often considerably stronger, harder and stiffer than the hydrated cement paste. As a result, an optimized aggregate gradation in concrete can minimize the requirement of cement paste and maximize the compressive strength, increase the abrasion resistance of concrete and modulus of elasticity of concrete [6]. Aggregate size and gradation can also influence other durability problems in concrete such as susceptibility to D-cracking and alkali-silica reaction. However, these durability problems have historically been minimal to non-existent in South Carolina and therefore will not be dealt with in this research investigation.

1.2 Aggregate Gradation and Its Specifications

The importance of aggregate gradation in concrete proportioning was first recognized by Fuller and Thompson in 1907 [9]. They developed an ideal gradation curve based on maximum density. Further work on aggregate gradation based on density was conducted by Talbot and Richart in 1923 [10]. Subsequently several other aggregate gradation concepts evolved including optimizing surface area, fineness modulus, minimizing particle interference and others. A comprehensive review of literature pertaining to aggregate gradation for concrete was recently conducted by Richardson in 2005 [11]. Modern concepts pertaining to aggregate gradation that have recently evolved include Shilstone method of workability and coarseness charts, 8-to-18 gradation band and FHWA 0.45 power gradation chart. These methods are employed by some state highway agencies in specifying aggregate gradation for portland cement concrete mixtures, however there is no consensus among specifying agencies as which method is the most appropriate. A significant number of state highway agencies still adopt standard ASTM C 33 specifications for aggregate gradation or its variations.

Aggregates used in concrete are typically classified as coarse aggregate (> # 4 sieve) and fine aggregates (# 4 sieve - # 200 sieve) depending on their particle size. The presence of material finer than 75 microns (No. 200 sieve) in concrete aggregates is typically considered as deleterious in achieving desired rheological, mechanical and durability properties of concrete. Therefore, a limit on maximum allowable percent is placed on this fine fraction to limit its impact.

Aggregate gradations for coarse and fine aggregates have historically been specified separately. For instance, the ASTM C 33-08, AASHTO M 6-08, M 43-05, and M 80-08 specify fine and coarse aggregate gradations separately that are suitable for use in hydraulic cement concrete. Some state agencies have their own specifications for aggregate gradations, depending on the experience with the local aggregate sources. For instance South Carolina specifies coarse and fine aggregate gradations as per Appendix A-4 and A-5 of SCDOT 2007 Standard Specification for Highway Construction, respectively (see Tables 1 and 2).

Table 1. SCDOT Coarse Aggregate Gradation Requirements

Gradation of Coarse Aggregates Percentage by Weight Passing Sieves Having Square Openings										
Sieve Designation	Aggregate No.									
	CR-14	5	56	57	67	6M	8M	78	789	89M
2-inch	100	--	--	--	--	--	--	--	--	--
1 ½ –inch	95 – 100	100	100	100	--	--	--	--	--	--
1-inch	70 – 100	90 – 100	90 - 100	95 - 100	100	100	--	--	--	--
¾-inch	--	20 – 55	40 - 85	--	90 – 100	90 – 100	100	100	100	--
½-inch	35 – 65	0 – 10	10 – 40	25 – 60	--	--	95 – 100	90 – 100	95 – 100	100
3/8-inch	--	0 – 5	0 – 15	--	20 – 55	0 – 20	75 – 100	40 – 75	80 – 100	98 – 100
No.4	10 – 40	--	0 – 5	0 – 10	0 – 10	0 – 5	10 – 35	5 – 25	20 – 50	20 – 70
No.8	--	--	--	0 – 5	0 – 5	--	--	--	--	2 – 20
No.16	--	--	--	--	--	--	0 – 5	0 – 5	0 – 6	--
No.100	--	--	--	--	--	--	0 – 2	--	0 – 2	0 - 3

Table 2. SCDOT Fine Aggregate Gradation Requirements

Gradation of Fine Aggregates				
Percentage by Weight Passing Sieves Having Square Openings				
Sieve Designation	Aggregate No.			
	FA-10	FA – 10M	FA-12	FA-13
½ inch	--	--	--	--
3/8 inch	100	100	100	100
No. 4	96 – 100	95 – 100	90 – 100	90 – 100
No. 8	75 – 100	84 – 100	--	--
No. 16	55 – 98	45 – 95	50 – 86	40 – 80
No. 30	25 – 75	25 – 75	--	--
No. 50	5 – 30	8 – 35	2 – 20	0 – 10
No. 100	0 – 9	0.5 – 20	0 – 5	0 – 3
No. 200	0 - 3	0 - 10	--	--

*Dust of fracture essentially free from clay or shale, final job site testing only.

It should be noted that some states are specifying optimized aggregate gradations that are based on combined gradation of coarse and fine aggregates. For instance, Oklahoma DOT allows the use of combined grading of coarse and fine aggregates in portland cement concrete that meets specific requirements. Such requirements are based on established aggregate gradation controls such as (i) Coarseness/Workability Charts (Shilstone method), (ii) FHWA 0.45 Power Curve and (iii) 8-to-18 chart (Percent Retained Chart).

Typically, gradation specifications allow aggregate to have a range of percent passing values on different sieve sizes. The allowable range of percent passing on each of the sieve sizes is generous enough to permit multiple aggregate sources at any location to satisfy the grading requirements; however, the limitations on gradation also ensure that the concrete manufactured with those aggregates will achieve desired properties. Some agencies have adopted limits on fineness modulus of aggregates as a basis for penalizing contractors for excessive deviation in gradations. For instance, MnDOT imposes a limit on fineness modulus of fine aggregate between 2.3 to 3.1, with stiff penalties when the fineness modulus deviates more than 0.20. However, the correlation between compliance with such specifications and the variation in quality of concrete is not established.

The boundaries placed on aggregate gradation in standard specifications have been established through empirical basis. While the influence of out-of-specification aggregate gradation on different rheological, mechanical and durability properties of concrete has been qualitatively appreciated, the quantitative effects of a failed aggregate on different properties of concrete has not been clearly established. More importantly, the extent of deviation from the standard grading requirement before which any adverse effects on properties of concrete become apparent has not been quantitatively approached. Understandably, this is a complex problem and the influences of aggregate gradation on specific properties might depend on type of concrete mix and the relative proportions of all the other ingredients.

1.3 Failure to Meet Aggregate Gradation Specifications

There have been a growing number of instances when aggregates sampled in the field at the time of placement of portland cement concrete (PCC) have failed to meet the SCDOT standard gradation requirements. A summary of submittals between the months of May 2009 through July 2009 that have failed to meet the coarse and fine aggregate gradations is provided in Tables 3 and 4, respectively.

Table 3. Failed Sieves and the % Deviation in Coarse Aggregate Gradations from Upper and Lower Limits for Different Sources

Gradation	Coarse Aggregate Source (Aggregate #)														
	A(67)	B(57)	C(57)	D(67)	E(67)	F(67)	G(57	H(67)	I(57)	J(67)	K(57)	L(67)	M(57)	N(67)	O(57)
%Passing 2”															
% Passing 1”															
% Passing ¾”				-1											
% Passing½”		+4	-11				+5		-8		-2		-2		
% Passing3/8”	-4			-6	-2	-3		+6		-6		-8			
% Passing No.4							+8							+5	+3
% Passing No.8							+3							+3	+1
% Passing No.16															
% Passing No.100															

Table 4. Failed Sieves and the % Deviation in Fine Aggregate Gradation (FA-10) from Upper and Lower Limits for Different Sources

Sieve Size	Aggregate Source									
	A	B	C	D	E	F	G	H	I	J
% Passing 3/8”										
% Passing No.4										
% Passing No.8										
% Passing No.16			-2				+4	-7		
% Passing No.30			-3	-4	+4			-6		
% Passing No.50	+5	+4		-2		+8			+11	+5
% Passing No. 100	+1					+1			+1	
% Passing No.200										

A close observation of the data in Table 3 suggests that majority of coarse aggregates failed on one or two sieve sizes (typically ½" and 3/8"), and by a margin that is less than 8% from the upper and lower limits of acceptable cumulative percent passing. Similarly, an inspection of data in Table 4 indicates that majority of fine aggregates failed on two sieve sizes (typically two of No. 16, No. 30, No. 50 sieves) by a margin that is less than 8% from the upper and the lower limits of acceptable cumulative percent passing. Even though the aggregates listed in Tables 3 and 4 failed to meet the gradation requirements, the decision to approve or reject these aggregates for use in PCC is made at SCDOT's discretion. However, the lack of adequate knowledge in understanding the impact of such deviations in aggregate gradations on properties of PCC has made it difficult for SCDOT to provide a sound basis for accepting or rejecting the concrete.

The proposed research study aims to investigate the sensitivity of selected concrete properties to variations in the gradations of coarse and fine aggregates, with emphasis on gradations both within and beyond the acceptable limits. The proposed research will attempt to define the maximum allowable deviations from the specified gradation and the consequences of such deviations on plastic and hardened properties of concrete.

1.4. Objectives

The principal objectives of this research study are:

(i) To determine the influence of variations in the gradation of coarse and fine aggregate out of the specification limits on the plastic and hardened properties of portland cement concrete.

(ii) Develop a methodology to limit the acceptable deviation in aggregate beyond the specification limits.

1.5 Scope of the Study

Considering the vast number of potential variables that impact the performance of concrete, the scope of this investigation was limited to the following:

1. Two coarse aggregates and two fine aggregates were employed in this study. The two coarse aggregates were crushed granites and two sands were natural siliceous river sands. No manufactured sands were employed in this study.
2. The gradations of the aggregates employed in this study were fabricated by first sieving the as-obtained aggregates into individual size fractions and them re-proportioning them to a specific gradation.
3. Failures in aggregate gradations were incorporated on only two selected sieves at one time. This enabled a careful control on the deviations in the aggregate gradation.
4. In order to minimize the impact of other variables all concrete mixtures were proportioned at a w/c ratio of 0.50 in this study. No other chemical admixtures were used with exception of a superplasticizer (at a constant dosage level in all mixtures). No supplementary cementing materials were employed in this study.
5. Considering that the acceptable gradation limits in the existing standards represents a fairly large window of percent passing on any given size, it was considered appropriate to employ three control gradations of aggregates in this study. Two control gradations embraced the absolute limits of acceptable gradation on either side of the median value and the third control gradation was selected to represent the median size within the acceptable limit on each sieve size. Therefore, any concrete mixture employing an aggregate gradation that failed to meet a specification could be compared fairly with a concrete mixture that contained the most appropriate control aggregate gradation that was closest to the failed gradation.

2.0 EXPERIMENTAL MATERIALS AND MIXTURE PROPORTIONS

The materials used in this study include ASTM Type I cement (high-alkali), reagent grade calcium hydroxide, two fine aggregates from different sources, two coarse aggregates from different sources and superplasticizers.

2.1 Cement

An ASTM Type I high-alkali cement having a Na_2O equivalent of 0.82% (Na_2O_{eq}) and an autoclave expansion of 0.08% was used in this study. The cement was obtained from Lehigh Cement Company from their Evansville Plant in Pennsylvania. The chemical composition of this cement is provided in Table 5.

Table 5. Chemical Composition of portland cement

Oxides	**Oxide composition (% by mass)**
SiO_2	19.78
Al_2O_3	4.98
Fe_2O_3	3.13
CaO	61.84
Alkali (Na_2Oeq.,%)	0.82
SO_3	4.15
MgO	2.54
Carbon	-
Available alkali	-
Loss on ignition	1.9
Insoluble residue	0.25
C_3A	8
C_3S	52

2.2 Coarse Aggregates

Two coarse aggregates (Aggregate 1 and Aggregate 2) were selected randomly from different sources so that the properties of concrete produced using these aggregates vary significantly. The as-received aggregates were first washed on a No. 4 sieve to remove dust particles and excessive fine materials. The washed aggregate was then kept in an oven maintained at a constant temperature of 105^0 C to remove moisture and dry aggregates. The properties of the coarse aggregates were then determined as per the ASTM standard test procedures before using it in concrete. Basic information on the two coarse aggregates is provided below:

1) *Aggregate 1:* The aggregate 1 was crushed granite from Sandy Flat Quarry in South Carolina, operated by Hanson Aggregates Southeast, LLC. The specific gravity of this aggregate is 2.60 and its water absorption was found to be 0.65%.
2) *Aggregate 2:* The aggregate 2 was obtained from Martin Marietta Cayce Quarry, South Carolina. The specific gravity of this aggregate is 2.60 and its water absorption was found to be 0.80%

Results from the sieve-analysis of these coarse aggregates, as per the ASTM C 136 specifications, are shown in Figure 1. As this figure shows, both coarse aggregates were of No. 57 gradation.

2.3 Fine Aggregates

The fine aggregates used in this study were natural siliceous sand from two different sources. The as-received sands were first washed to remove dust and organic materials. The wet sand was then dried in the oven to remove moisture, before determining its properties. The information pertaining to these two sands is provided below:

(a) *Sand 1:* The sand 1 is naturally available river sand obtained from a local ready mix concrete producer in Seneca, South Carolina. The specific gravity of this sand is 2.62 and its water absorption was found to be 1.80%.

(b) *Sand 2:* The sand 2 was obtained from Glasscock pit in Sumter, South Carolina. The specific gravity of this sand is 2.65 and its water absorption was found to be 0.20%.

The sieve analysis performed on these sands is shown in Figure 2. As this figure shows, the average particle size of these sands was almost the same and equal to 650 microns. However, the particle size distribution of these sands varied. Sand 1 was found to be well graded than sand 2, with the gradation curve of the latter having steeper slope than that of the former.

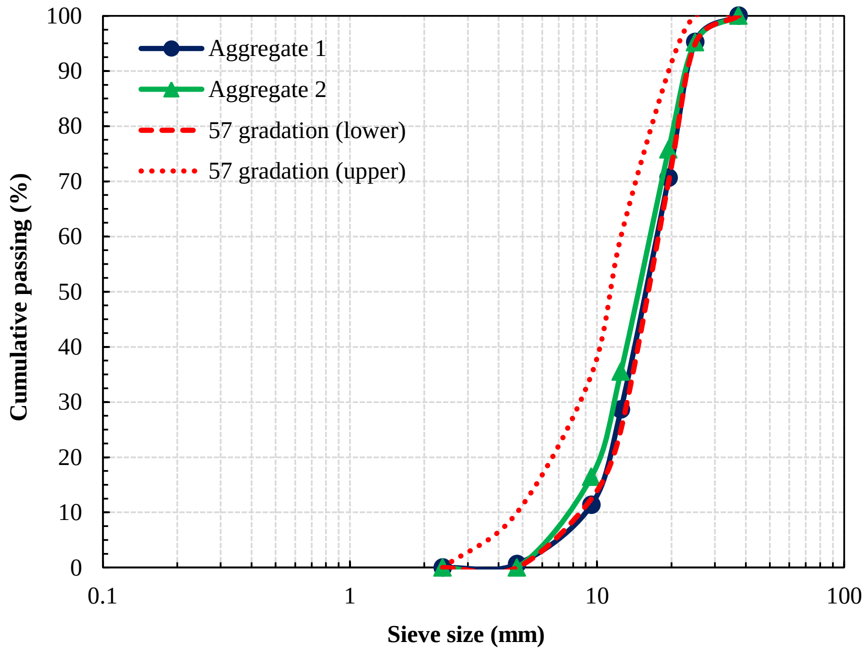


Figure 1. Sieve analysis of coarse aggregates

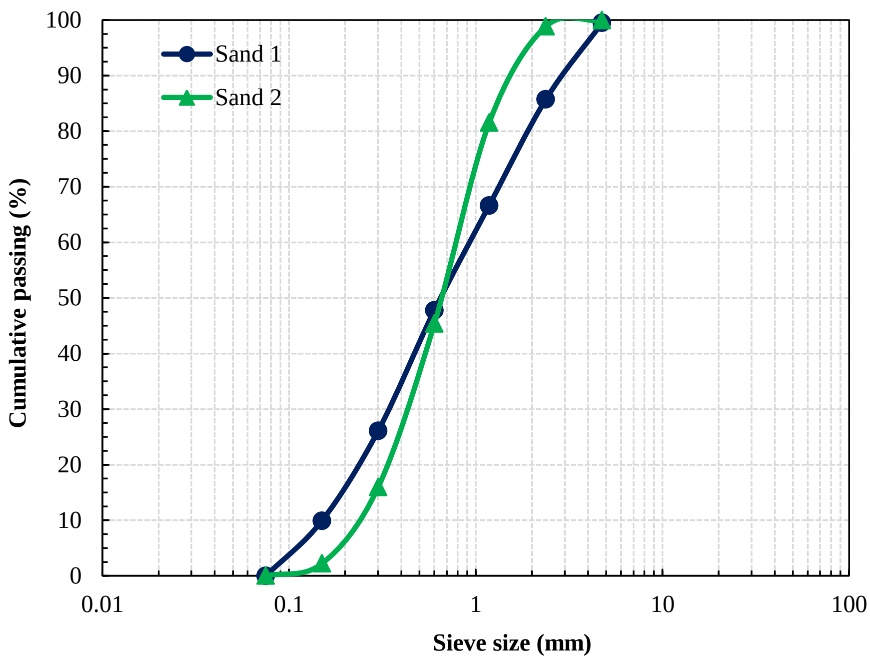


Figure 2. Sieve analysis of sand

2.4 Superplasticizer

The superplasticizer used in this study was a poly-carboxylate type, Glenium 7101 from BASF Construction Chemicals Limited. Its specific gravity was 1.05 and viscosity was 85 cps.

2.5 Mixture Proportions

The concrete mixture proportions used in this study were formulated based on SCDOT specifications for bridge applications, with a target 28-day compressive strength of 4,000 psi. The mixture proportions used in this study are shown in Table 6.

Table 6. Quantity of materials per unit volume of concrete

Material	Quantity of materials	
	lbs./yd^3	kg/m^3
Cement	612	363
Water	304	180
Fine aggregate	1150	682
Coarse aggregate	1777	1054

3.0 EXPERIMENTAL TEST METHODS

The different tests conducted to determine the fresh and hardened properties of concrete include slump, fresh air content, density, compressive strength, split tensile strength, modulus of elasticity, hardened air content, water absorption, rapid chloride ion permeation and shrinkage. The details of these test methods are presented below:

3.1 Fresh Properties

The fresh properties of concrete, specifically workability, density and air content, were determined based on the ASTM C 143, the ASTM C 192 and the ASTM C 187 test methods, respectively.

3.2 Compressive strength

The compressive strength test of concrete was conducted on 100 x 200 mm cylinders using the ASTM C 39 test procedure. To determine the effect of variation in the fine or coarse aggregate gradation on the rate of compressive strength development, the concrete mixtures were tested at 3, 7, 14 and 28 days of curing.

3.3 Static modulus of elasticity

The Static Modulus of Elasticity of the concrete specimens was determined using the ASTM C 469 test procedure. Prior to the start of the test, companion specimens were used to determine the ultimate compressive strength of concrete using the ASTM C 39 test procedure. The compressometer (acting as strain measuring equipment) was attached along the gauge length of the 100 x 200 mm cylinder specimens. The axis of the specimen was aligned with the center of thrust of the spherical seating upper bearing block of a hydraulically operated Universal Testing Machine (UTM). As the spherical-seated block was brought slowly to bear upon the specimen, adjustments were made to ensure uniform seating. The specimen was loaded two to three times before the actual readings were taken to ensure the proper seating of the gauges. Then, the load was applied gradually without shock at a constant rate of 35 $\pm$ 5 psi/s. The applied load and the corresponding strains were measured without any interruption until the load was equal to 40% of the ultimate load of the specimen. The static modulus of elasticity E, of the cylinder specimens was then calculated using the formula:

$$E = (S1-S2) / (\varepsilon 2-0.00005) \qquad \text{--- (1)}$$

where

*S*2 is the stress corresponding to 40 % of the ultimate load

*S*1 is the stress corresponding to a longitudinal strain, e 1, of 50 millionths, psi

ε 2 is the longitudinal strain produced by stress *S2*

3.4 Split tensile strength

The split tensile strength of concrete was conducted as per the ASTM C 496 after 28 days of curing of the concrete specimens. The size of the concrete specimens used was 100 x 200 mm cylinders. In this test, the load was applied without shock until the failure of the specimen. In addition, a constant rate of loading of 0.86-1.21 MPa/min was maintained until the failure of the specimens. The split tensile strength was calculated by using the formulas given in the ASTM C 496 test methods.

3.5 Water absorption

The water absorption test was conducted on concrete cylinders of size 50 mm dia. x 300 mm long after 28 days curing period as per the ASTM C 642 test method. The specimens were initially heated in an oven for 24 hours at a temperature of $105^0 \pm 2^0$ C. They were then removed and immersed in water, and their masses measured after 24 hours. The water absorption value of the various concretes was then calculated by determining the percentage increase in the mass of the specimens after immersion in water for 24 hours.

3.6 Rapid Chloride Ion Permeability (RCP)

In this test, the ability of concrete to resist penetration by harmful chloride ions was measured after 56 days of curing of the concrete specimens. This test was conducted as per the ASTM C 1202 test method. Three concrete cylinder discs of 63.5 mm dia. x 100 mm height were cut from three standard 100 x 200 mm concrete cylinders. The 6-hr charge passed through concrete test specimens was reported as the rapid chloride ion permeability value.

3.7 Drying Shrinkage

The drying shrinkage of concrete was determined using the ASTM C 495 test procedure. In this test, concrete prisms of standard size 75 x 75 x 285 mm with gage studs were cast. After initial three days of curing in $Ca(OH)_2$ solution, the bars were taken out, wiped dry and initial expansion readings were noted. Then, the bars were immediately kept in an environmental chamber maintained at a temperature of 23^0 C and at a relative humidity of 50%. Subsequent readings were taken at regular periods until 180 days and the shrinkage strains were calculated from the percentage shrinkage expansion values.

4.0 EXPERIMENTAL PROGRAM

The comprehensive investigation conducted to determine the effect of aggregate gradation on the properties of portland cement concrete was divided into two sections. The first section involved investigations with portland cement concrete produced using the first set of coarse and fine aggregates namely, aggregate 1 and sand 1, respectively, and the second section involved investigations with concrete produced using the second set of coarse and fine aggregates namely, aggregate 2 and sand 2, respectively. In order to understand the effect of coarse aggregate gradation on the properties of concrete, a standard fine aggregate gradation was used in the mixtures. Similarly, to understand the effect of fine aggregate gradation on the properties of concrete, a standard coarse aggregate gradation was used. In this way, only the gradation of coarse or fine aggregate was varied and the total content of cement, water, fine and coarse aggregates were held constant in all the mixtures.

For investigations with the first set of aggregates, a total of 17 concrete mixtures were produced to determine the influence of gradation on specific properties of concrete. Of these mixtures, 9 mixtures were used to determine the effect of fine aggregate gradation and the remaining 9 mixtures were used to determine the effect of coarse aggregate gradation. Similarly, another 17 concrete mixtures were produced for performing similar investigations with the second set of aggregates available. The specific tests performed with each set of aggregates are shown in Tables 7 and 8.

Table 7. List of tests performed with first set of aggregates

Sl. No.	Name of tests	Standards
1.	Workability	ASTM C 143
2.	Fresh air content	ASTM C 231
3.	Density (dry-rodded unit weight)	ASTM C 29
4.	Compressive strength	ASTM C 39
5.	Split tensile strength	ASTM C 496
6.	Modulus of elasticity	ASTM C 469
7.	Rapid chloride permeation ion test	ASTM C 1202
8.	Water absorption	ASTM C 642
9.	Drying shrinkage	ASTM C 596
10.	Hardened air content	ASTM C 457

Table 8. List of tests performed with the second set of aggregates

Sl. No.	Name of tests	Standards
1.	Workability	ASTM C 143
2.	Fresh air content	ASTM C 231
3.	Density (dry-rodded unit weight)	ASTM C 29
4.	Compressive strength	ASTM C 39
5.	Split tensile strength	ASTM C 496
6.	Modulus of elasticity	ASTM C 469
7.	Rapid chloride permeation ion test	ASTM C 1202
8.	Water absorption	ASTM C 642
9.	Hardened air content	ASTM C 457

4.1 Selection of coarse aggregate gradations

4.1.1 Control gradation for coarse aggregates

The gradations of aggregate 1 and 2 were selected by considering the South Carolina Department of Transportation (SCDOT) standard coarse aggregate gradation specifications as shown in Table 1. In this study, Aggregate No. 57 gradation was used as standard coarse aggregate gradation. The gradation for the control was selected primarily based on the lower, average and upper values of the percentage weight passing through the specific sieves for the No. 57 gradation, with slight modification. A plot of the lower, average and upper values of the No. 57 gradation is shown in Figure 3. As this figure shows, the majority of coarse aggregates ranged in size between 19.5 mm and 9.5 mm, and only a small fraction was either finer than 9.5 mm or coarser than 19.5 mm. Since small quantities of fine or coarse particles can significantly affect the deviations in the test results, the aggregate sizes below 9.5 mm or above 19.5 mm were discarded. The lower, average and upper values of the resulting aggregate gradations having only three size fractions of aggregates (9.5 mm, 12.5 mm and 19.5 mm) were considered as the Control 1, Control 2 and Control 3 gradations as shown in Figure 4.

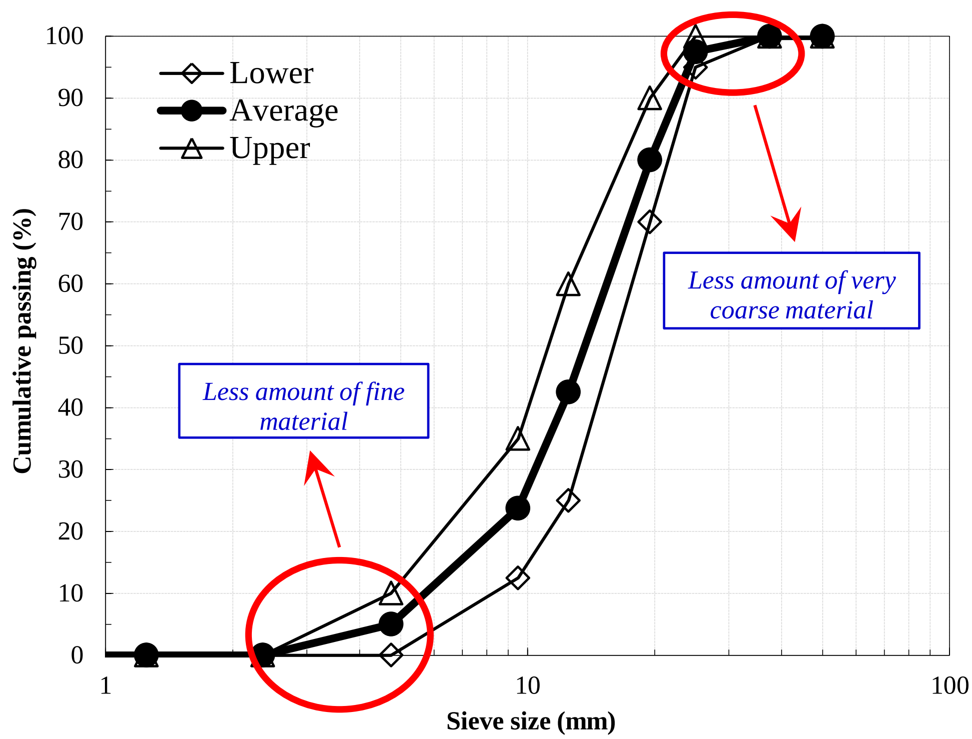


Figure 3. Coarse aggregate gradation for upper, middle and lower values of 57 gradation

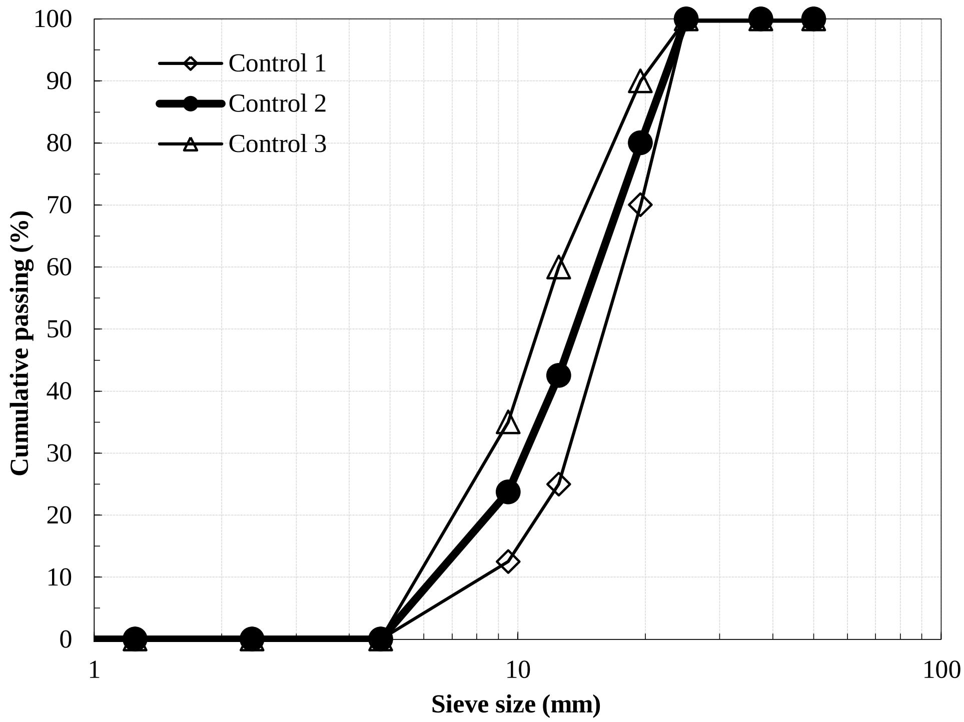


Figure 4. Three control gradations for coarse aggregate used in this study

4.1.2 Failed gradation for coarse aggregate

A review of submittals to SCDOT between May and July 2009 that have failed to meet the gradation specifications for No. 57 aggregate (provided in Table 3) showed that the specific sieves on which the aggregates failed to meet the requirements were ¾ in., ½ in., 3/8 in., No. 4 and No. 8. Since the majority of coarse aggregate sizes belonging to either No. 57 or No. 67 standard gradations are ¾ in., ½ in. and 3/8 in., the aggregate gradations which failed on No. 4 and No. 8 sieves were not considered when selecting failed gradations. Failed gradations can then be obtained by reducing or increasing the quantity of aggregates that are finer than ½" and correspondingly increasing or decreasing the quantity of aggregates in the subsequent sieves that are above or below the ½" sieve in such a way that the total quantity of aggregates passing through all the sieves is constant. Such a calculation can be performed for both Control 1 and Control 3 gradation to obtain "Negative" (NEG) and "Positive" (POS) failed gradations as shown in Tables 9 and 10 below, respectively.

Table 9. Control-1 gradation and its respective failed gradations.

Sieve designation	**Sieve size**	**Percentage passing through each sieve (%)**			
	mm	**Control – 1**	**Neg. 6**	**Neg. 12**	**Neg. 18**
2 in.	50	100	100	100	100
1 ½ in.	37.5	100	100	100	100
1	25	100	100	100	100
¾ in.	***19.5***	***70***	***76***	***82***	***88***
½ in.	***12.5***	***25***	***19***	***13***	***7 (Not possible)***
3/8 in.	***9.5***	***12.5***	***12.5***	***12.5***	***12.5***
No. 4	4.75	0	0	0	0
No. 8	2.36	0	0	0	0
No. 16	1.25	0	0	0	0
No. 30	0.60	0	0	0	0

Table 10. Control-3 gradation and its respective failed gradations

Sieve designation	**Sieve size**	**Percentage passing through each sieve (%)**			
	mm	**Control - 3**	**Pos. 6**	**Pos. 12**	**Pos. 18**
2	50	100	100	100	100
1.5	37.5	100	100	100	100
1	25	100	100	100	100
¾ in.	***19.5***	***90***	***90***	***90***	***90***
½ in.	***12.5***	***60***	***66***	***72***	***78***
3/8 in.	***9.5***	***35***	***29***	***23***	***17***
No. 4	4.75	0	0	0	0
No. 8	2.36	0	0	0	0
No. 16	1.25	0	0	0	0
No. 30	0.6	0	0	0	0

As shown in Table 9, the percentage passing through the ½" sieve for the control 1 gradation was decreased by 6% (i.e., from 25% to 19%) and 12% (i.e., from 25% to

13%) to obtain Neg. 6 and Neg. 12 gradations, respectively. These deficits in the ½" coarse aggregate of Neg. 6 and Neg. 12 gradations was followed by a subsequent increase in the quantity of their ¾" coarse aggregate by 6% (i.e., from 70% to 76%) and 12% (i.e., from 70% to 82%), respectively. In this way, the total quantity of aggregates passing through all the sieves was held constant. It is to be noted that a decrease in the percentage passing through the ½" sieve for the control 1 gradation by 18% (i.e., from 25% to 7%) is not possible, as the percentage passing through the sieve below it is 12.5% (higher than 7%). Thus, a total of two gradations (Neg. 6 and Neg. 12) that failed to meet Control 1 gradation were formed as shown in Figure 5.

Similarly the Table 10 shows that the percentage passing through the ½" sieve for the control 3 gradation was increased by 6% (i.e., from 60% to 66%), 12% (i.e., from 60% to 72%) and 18% (i.e., from 60% to 78%) to obtain Neg. 6, Neg. 12 and Neg. 18 gradations, respectively. This surplus in the ½" coarse aggregate of Pos. 6, Pos. 12 and Pos. 18 gradations was followed by a subsequent decrease in the quantity of their 3/8" coarse aggregate by 6% (i.e., from 35% to 29%), 12% (i.e., from 35% to 23%) and 18% (i.e., from 35% to 17%), in order for the total quantity of aggregates to be constant. Thus, a total of three gradations (Pos. 6, Pos. 12 and Pos. 18) that failed to meet Control 3 gradation were formed as shown in Figure 6. It can be seen in Figures 5 and 6, the deficit or surplus of coarse aggregates in the ½" sieve has resulted in a gradation that falls completely out of the standard specifications.

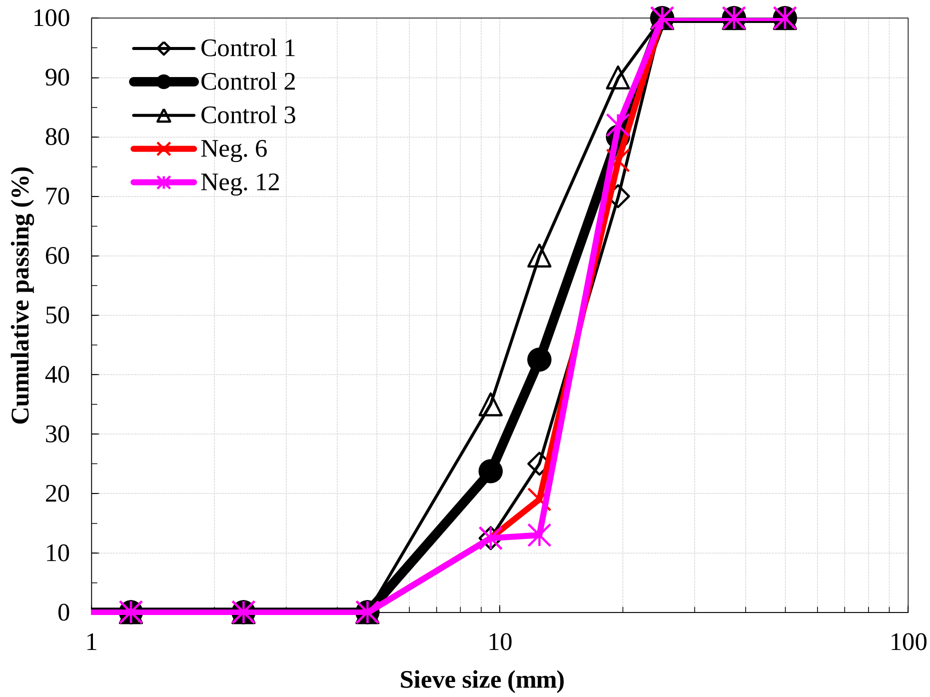


Figure 5. Comparison of negative gradation with control 1 gradation

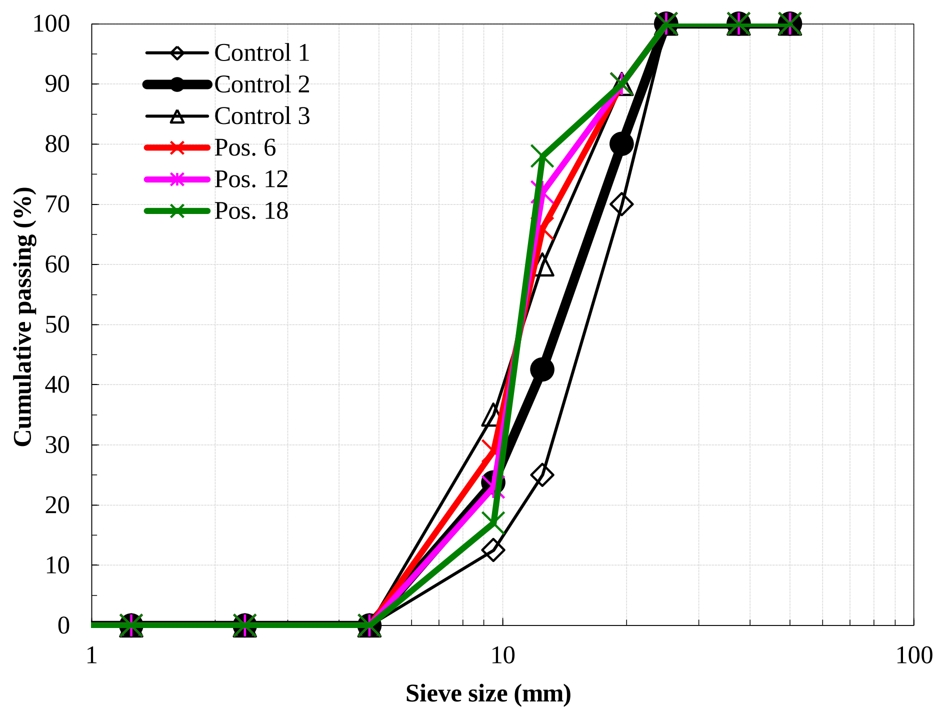


Figure 6. Comparison of positive gradation with control 3 gradation

4.2 Selection of fine aggregate gradations

4.2.1 Control gradation for sand

The gradations of sands 1 and 2 were selected by considering the South Carolina Department of Transportation (SCDOT) standard fine aggregate gradation specifications provided in Table 4. This specification includes a set of four different standard fine aggregate gradations, with upper and lower limits specified for specific sieve sizes. In this study FA-10 gradation was selected as standard fine aggregate gradation. Three Control gradations for the sands were selected primarily based on the lower, average and upper values of the cumulative percentage passing through specific sieves for the FA-10 gradation, with slight modification. A plot of the lower, average and upper values of the FA-10 gradation is shown in Figure 7.

As this figure shows, the majority of sand particles range in size between No. 8 and No. 50 sieves, and only small fraction is either finer than No. 50 or coarser than No. 8 sieve. Since small quantities of fine or coarse particles can significantly affect the test results, the sand fractions of size below No. 50 or above No. 8 were discarded in formulating the Control and failed gradations of sand. The lower, average and upper limits of acceptable cumulative percent passing values of the resulting aggregate gradations, having only four sizes of fine aggregates (i.e. No. 8, No. 16, No. 30 and No. 50), were considered as the Control 1, Control 2 and Control 3 gradations as shown in Figure 8.

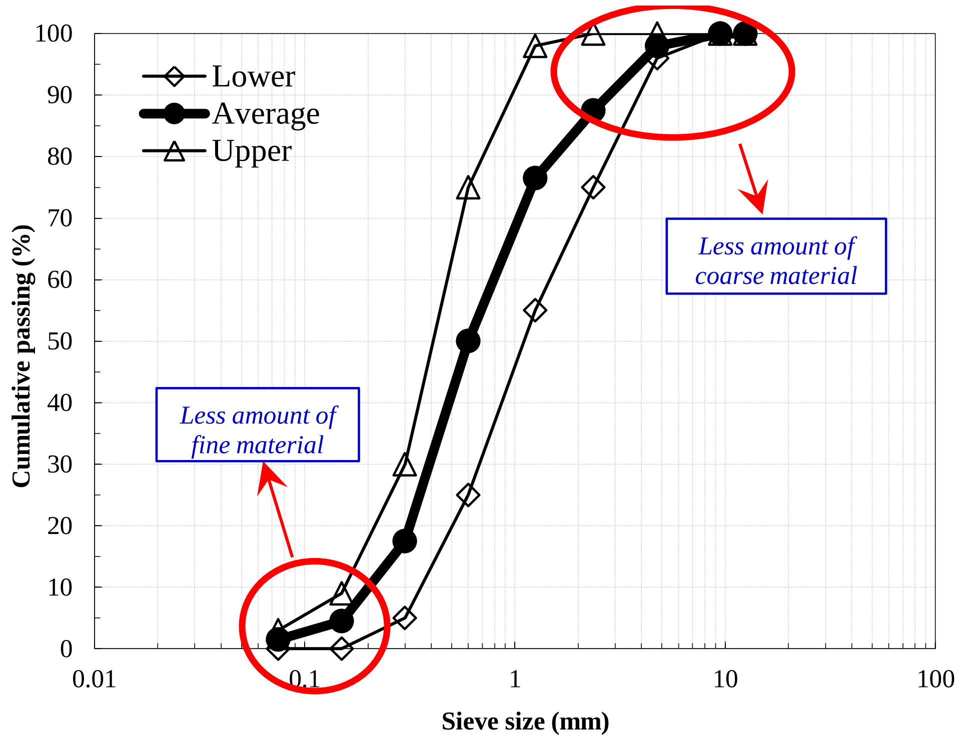


Figure 7. Sand gradation for upper, middle and lower values of FA-10 gradation

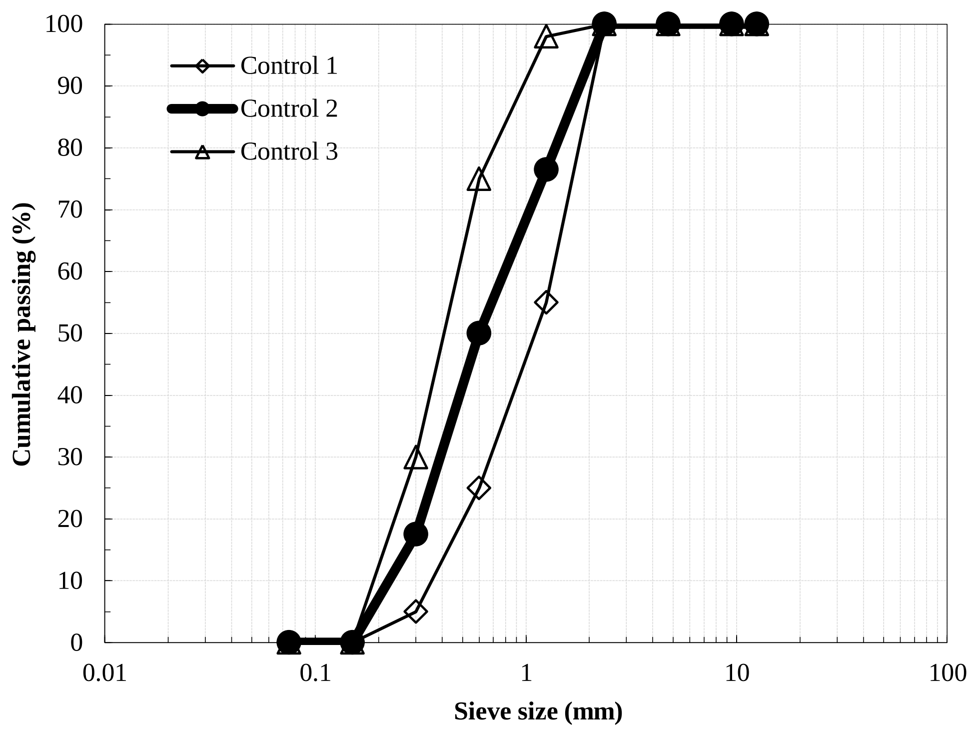


Figure 8. Three control gradations for sand used in this study

4.2.2 Failed gradation for sand

The summary of submittals to SCDOT between the months of May 2009 through July 2009 that failed to meet the standard fine aggregate gradation specification is provided in Table 4. As this table indicates, the specific sieves on which the aggregates failed to meet the requirements were No. 16, No. 30, No. 50 and No. 100. Since the majority of failed size fractions were on sieve sizes No. 16, No. 30 and No. 50 sieves, the gradations which failed on No. 8 and No. 100 sieves were not considered in this study. Since a majority of failed gradations occurred on No. 30 sieve, the failed gradation can be obtained by reducing or increasing the quantity of aggregates finer than this sieve and correspondingly increasing or decreasing the quantity of sand in the subsequent sieves above or below this sieve in such a way that the total quantity of sand is constant. Such a calculation can be performed for both Control 1 and Control 3 gradation to obtain "Negative" and "Positive" failed gradations as shown in Tables 11 and 12 below, respectively.

Table 11. Control 1 gradation and its respective failed gradations

Sieve Designation	Sieve size	Percentage passing through each sieve (%)		
	mm	Control 1	Neg. 6	Neg. 12
½ in.	12.5	100	100	100
3/8 in.	9.5	100	100	100
No. 4	4.75	100	100	100
No. 8	2.36	100	100	100
No. 16	1.25	55	61	67
No. 30	0.60	25	19	13
No. 50	0.30	5	5	5
No. 100	0.15	0	0	0
No. 200	0.075	0	0	0

Table 12. Control 3 gradation and its respective failed gradations

Sieve Designation	Sieve size	Percentage passing through each sieve (%)		
	mm	Control 3	Pos. 6	Pos. 12
½ in.	12.5	100	100	100
3/8 in.	9.5	100	100	100
No. 4	4.75	100	100	100
No. 8	2.36	100	100	100
No. 16	1.25	98	98	98
No. 30	0.60	75	81	87
No. 50	0.30	30	24	18
No. 100	0.15	0	0	0
No. 200	0.075	0	0	0

As seen in Table 11, the percentage passing through the No. 30 sieve for the Control 1 gradation was decreased by 6% (i.e., from 25% to 19%) and 12% (i.e., from 25% to 13%) to obtain Neg. 6 and Neg. 12 gradations, respectively. This deficit in the No. 30 particles of Neg. 6 and Neg. 12 gradations was followed by a subsequent increase in the quantity of their No. 16 sand fractions by 6% (i.e., from 55% to 61%) and 12% (i.e., from 55% to 67%), respectively. In this way, the total quantity of sand was held constant. Though reducing the quantity of sand fractions of No. 30 sizes to 18% was possible, it was not necessary to reduce the sand fractions below 12%, as the maximum deviation in the percentage passing of sand grains is only +11 as seen from Table 4. Thus, a total of two gradations (Neg. 6 and Neg. 12) that failed to meet Control 1 gradation were formed as shown in Figure 9.

Similarly the Table 12 shows that the percentage passing through the No. 30 sieve for the control 3 gradation was increased by 6% (i.e., from 75% to 81%) and 12% (i.e., from 75% to 87%) to obtain Pos. 6 and Pos. 18 gradations, respectively. This surplus in the

No. 30 particles of Pos. 6 and Pos. 12 gradations was followed by a subsequent decrease in the quantity of their No. 50 size fractions by 6% (i.e., from 30% to 24%) and 12% (i.e., from 30% to 18%), in order for the total quantity of aggregates to be constant. Thus, a total of two failed gradations (Pos. 6 and Pos. 12) that failed to meet Control 3 gradation were formed as shown in Figure 10. It can be seen in Figures 9 and 10, that the deficit or surplus of coarser sized particles in the No. 30 sieve has resulted in a gradation that falls completely out of the standard specifications.

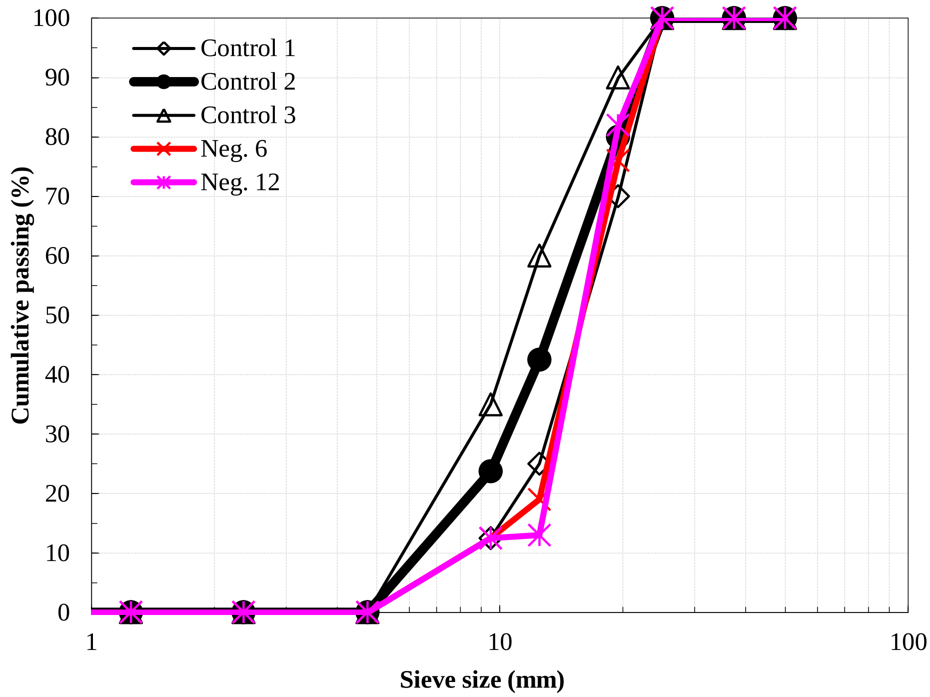


Figure 9. Comparison of negative gradation with control 1 gradation

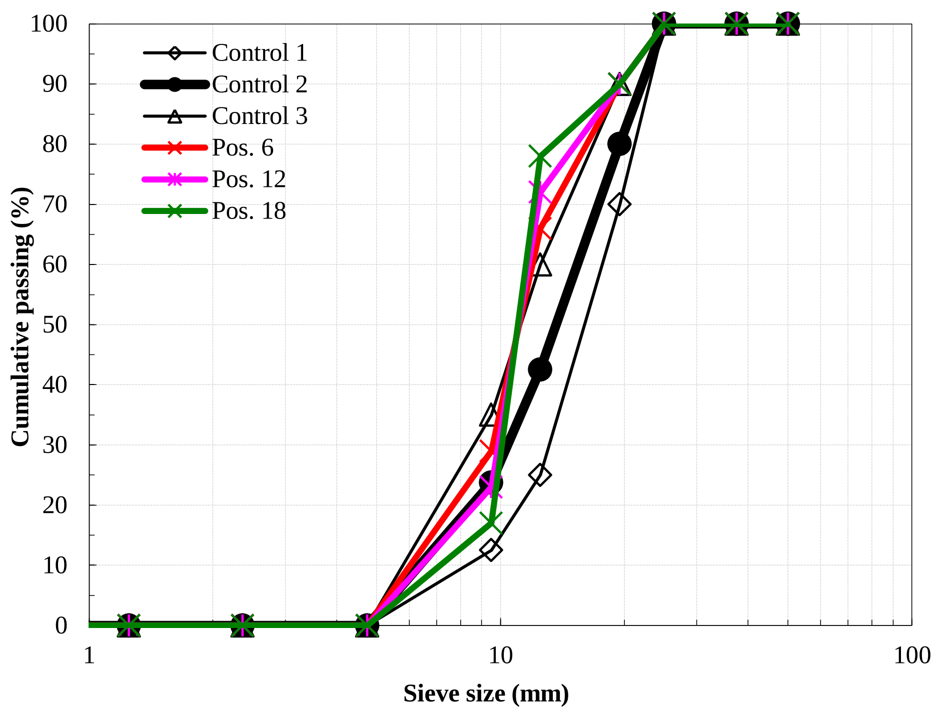


Figure 10. Comparison of positive gradation with control 3 gradation

5.0 RESULTS AND DISCUSSIONS

5.1 Effect of coarse aggregate gradation on specific properties of concrete

The effect of coarse aggregate gradation on specific properties of concrete was determined by using a constant fine aggregate gradation in all the mixtures. Since the quantity of all the ingredients remained constant in all the mixture and the only variable is the coarse aggregate gradation, its effect on portland cement concrete mixtures can be determined.

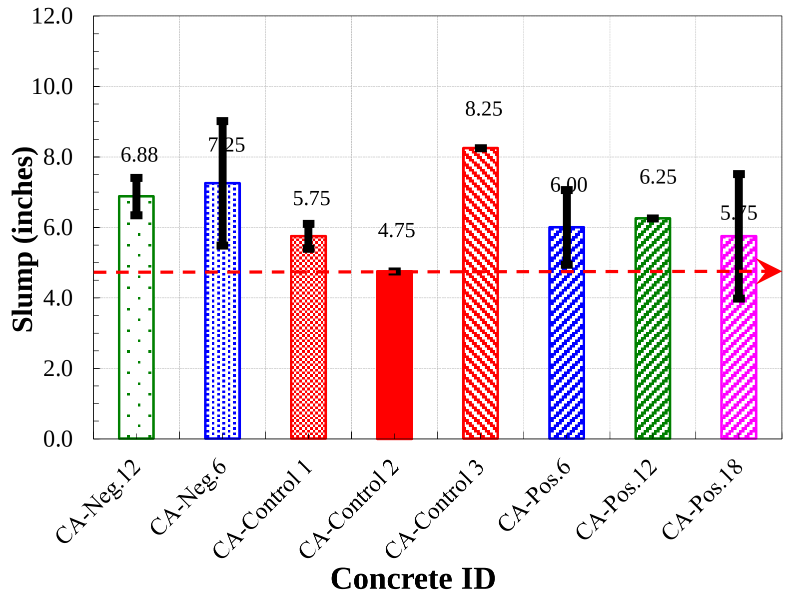
5.1.1 Slump

The effect of coarse aggregate (CA) gradation on the slump of concrete containing the 1st and 2nd set of aggregates is shown in Figures 11 (a) and 11 (b), respectively.

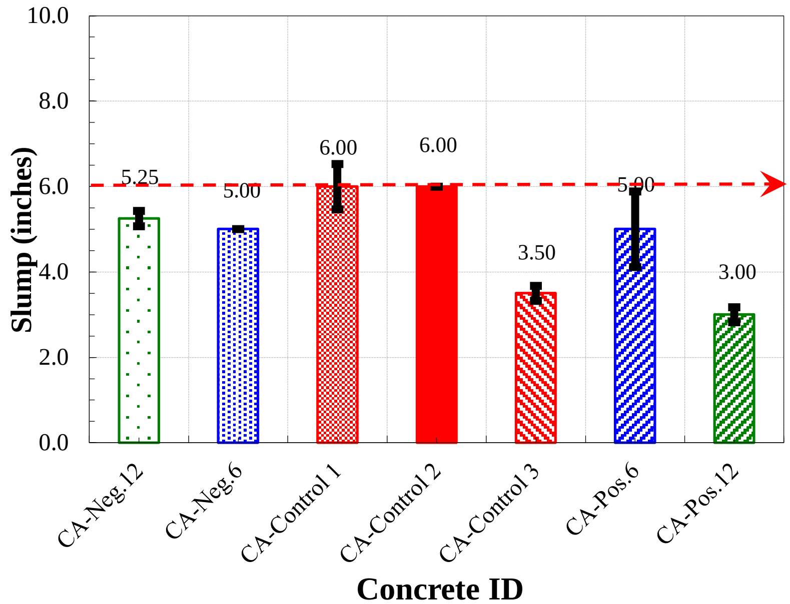
With the 1st set of aggregates shown in Figure 11 (a), the slump of CA-Control 2 concrete was found to be lower compared to other control concretes (Control 1 and Control 3) and also those that contained failed coarse aggregate gradations. The slump of concrete containing control 1, 2 and 3 coarse aggregate gradations were found to be 5.75, 4.75 and 8.25 inch, respectively. Considering only control concretes, the variation between the values of CA-Control 2 concrete and that of other control concretes (CA-Control 1 and CA-Control 3) was found to vary between 21%-74%, indicating that the deviation in the coarse aggregate gradation within the acceptable limits can still result in significant variation in the slump values of the control concretes. The slump of concretes containing negatively failed aggregate gradations (Neg. 6 and Neg. 12) was found to be higher than that of their control concrete (CA-Control 1) while the slump of concretes containing positively failed aggregate gradations (Pos. 6, Pos. 12 and Pos. 18) was found to be lower than that of control concrete (CA-Control 3). There is no specific trend observed in the slump values by varying the gradation beyond the control 1 or control 3 up to CA-Neg. 12 or CA-Pos. 18 concrete.

With the 2nd set of aggregates as shown in Figure 11 (b), the slump of CA-Control 2 concrete was found to be higher compared to other control concretes and those that contained failed coarse aggregate gradations. Similar to the results obtained with the previous aggregate set, the variation between the values of CA-Control 2 concrete and that of other control concretes (CA-Control 1 and CA-Control 3) was found to deviate significantly (0%-41%). The slump of concretes containing negatively failed aggregate gradations was found to be lower than that of their respective control concretes.

In the case of concretes containing positively failed aggregate gradation, the slump of CA-Pos. 6 and CA-Pos. 12 concretes was above and below that of Coarse Aggregate-Control 3 concrete, respectively. Similar to the 1st set of aggregates, there is no specific trend observed in the slump values by varying the aggregate gradation beyond the control 1 or control 3 gradations up to Neg. 12 or Pos. 12 gradations.



(a) With first set of aggregates (aggregate 1 and sand 1)



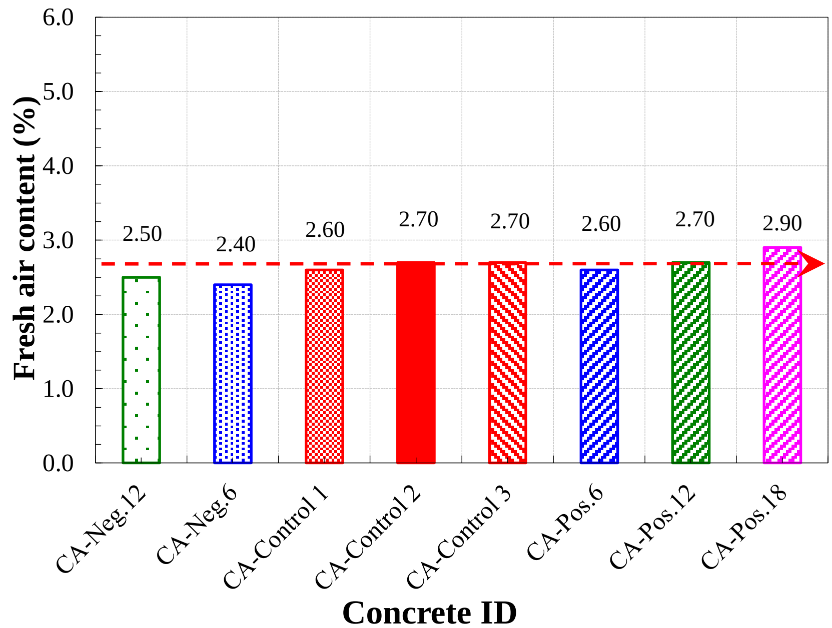
(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 11. Effect of coarse aggregate gradation on workability of concrete produced from different sets of aggregate

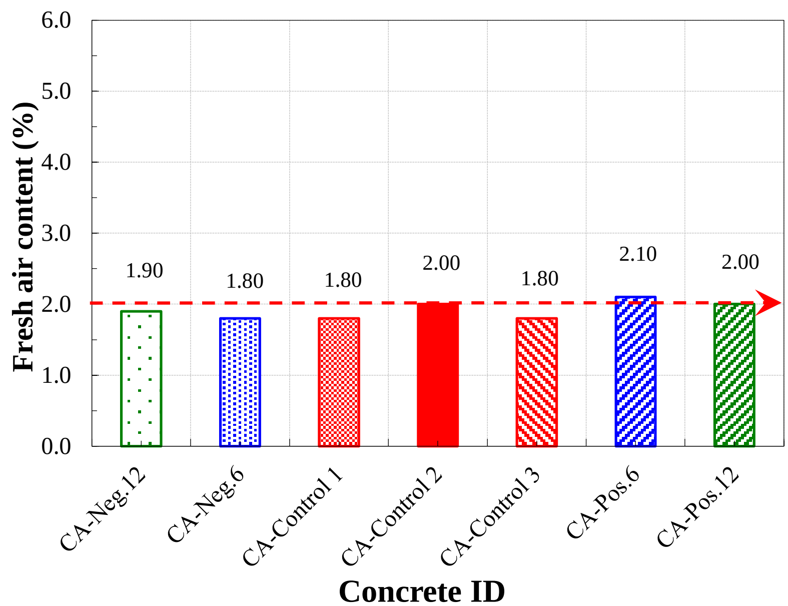
5.1.2 Fresh air content

The effect of coarse aggregate gradation on the fresh air content of concrete containing the 1st and 2nd set of aggregates is shown in Figures 12 (a) and 12 (b), respectively. It should be noted that no air-entraining agent was used in these concrete mixtures; however superplasticizer was used in all concrete mixtures at a constant but small dosage level (0.5% by weight of cement). It is therefore assumed that any air observed in the concrete mixtures was due to entrapped air and is a reflection of the influence of gradation of the aggregates on the concrete mixture.

With the 1st set of aggregates shown in Figure 12 (a), the fresh air content of control 2 concrete (2.70%) was found to be slightly higher or lower than the other control concretes and concretes containing failed aggregate gradation. The CA-control 1 and CA-Control 3 concretes deviated from the CA-Control 2 concrete by 0.1% and 0% air content levels, respectively. This indicates that the coarse aggregate gradation has minimal effect on the fresh air content of concrete. No definite trend in the fresh air content of concrete was observed while deviating beyond the control coarse aggregate gradations. Concrete mixtures containing the 2nd set of aggregates performed similar to the 1st set of aggregates, with very minimal change in the fresh air content values. The fresh air content of the CA-Control 2 concrete did not deviate much from that of other control and failed gradation concretes.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 12. Effect of coarse aggregate gradation on the fresh air content of concrete produced from different sets

5.1.3 Density and Yield

The effect of coarse aggregate gradation on the density and yield of concrete containing 1st and 2nd set of aggregates are shown in Tables 13 and 14, respectively.

Table 13. Density and yield of concrete containing 1st set of aggregates

Concrete ID	Density lb./ft^3	Yield (No Units)
CA-Neg.12	145.88	0.976
CA-Neg.6	145.20	0.980
CA-Control 1	145.77	0.976
CA-Control 2	146.08	0.974
CA-Control 3	144.50	0.985
CA-Pos.6	144.87	0.982
CA-Pos.12	144.88	0.982
CA-Pos.18	145.20	0.980

Table 14. Density and yield of concrete containing 2nd set of aggregates

Concrete ID	Density lb/ft^3	Relative yield No unit
CA-Neg.12	148.60	0.958
CA-Neg.6	148.00	0.962
CA-Control 1	148.30	0.96
CA-Control 2	147.60	0.964
CA-Control 3	147.50	0.965
CA-Pos.6	146.90	0.969
CA-Pos.12	147.80	0.963

Based on the results shown in Table 13 with the first set of aggregates, the density of concrete containing different coarse aggregate gradations were approximately equal to each other and there is no substantial variation in their densities. For example, the density of concrete containing the extreme gradations (CA-Neg. 12 and CA-Pos. 18) was found to be only 0.13% and 0.60% lower than that of the CA-Control 2 concrete, indicating that the deviation in the coarse aggregate gradation beyond the control gradations has very limited influence on the density of concrete. In addition, the relative yield of all the concrete was also found to be approximately equal and no specific trend was observed with the relative yield. The data on the yield of concrete supports the data on the density of concrete as expected.

The trends observed with the density of concrete containing the 2nd set of aggregates was similar to that containing the 1st set of aggregates as shown in Table 14, i.e., the density of different concrete mixtures were approximately equal. The yield of concrete also supported the density data, with less variation between each of the concrete mixtures.

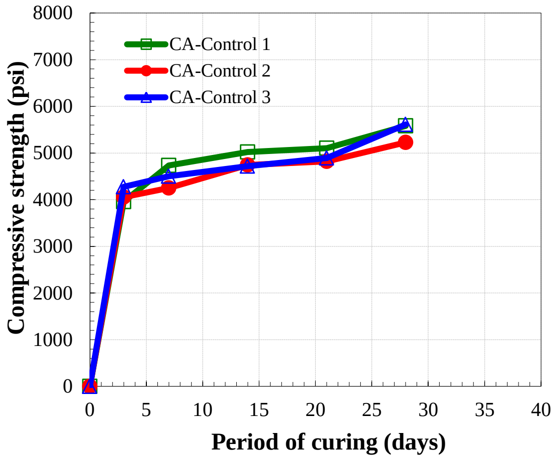
5.1.4 Rate of compressive strength development

The effect of coarse aggregate gradation on the rate of compressive strength development of concrete containing the 1st and 2nd set of aggregates is shown in Figure 13 and 14, respectively.

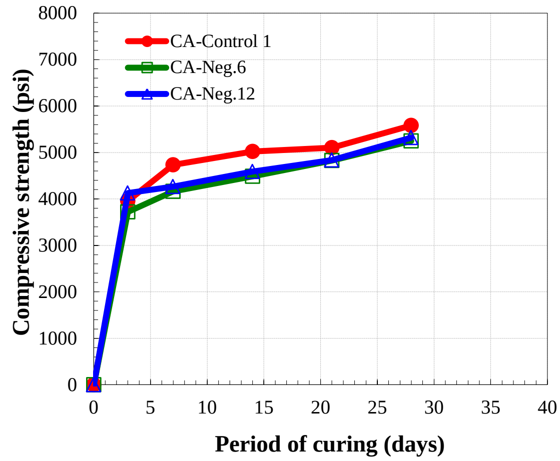
Based on the results from tests on the 1st set of aggregates as shown in Figures 13 (a) through (c), the compressive strength of different concretes increased with increase in the period of curing from 0 to 28 days, as expected. It can be observed that there is a steep increase in the compressive strength of concretes at early curing periods (3- or 7-day), while there is only a slight increase in the compressive strength of concretes at later curing periods. The early-age compressive strength of all the control concretes [as shown in Figure 13 (a)] was found to be more or less equal. Similarly, the early age compressive strength of control and failed gradation concretes [as shown in Figure1 13 (b) and 13 (c)], was also found to be approximately equal. As the compressive strength of all concretes at any early-age curing period is approximately equal, the variation in the coarse aggregate gradation has only a minimal influence on the early-age compressive strength of concrete.

In order to understand the effect of coarse aggregate gradation on the later-age compressive strength, a comparison of the 28-day compressive strengths of all the concretes was performed as shown in Figure 13 (d). As this figure shows, the compressive strength of different concretes ranged from 5225 psi to 5895 psi. Considering only the control concretes, the 28-day compressive strengths of CA-Control concretes ranged between 5225 psi and 5612 psi. This represents a range of 7.4%, which is within the normal range of variability that is expected of conventional concrete mixtures. This indicates that the deviation in the coarse aggregate gradation within the acceptable specification limits does not seriously affect the 28-day compressive strength of the control concretes. The compressive strength of concretes containing negatively failed aggregate gradations was found to be slightly lower (6%) than that of control concrete (CA-Control 1). In the case of positively failed aggregate gradation concretes, the compressive strength of CA-Pos. 6 concrete was slightly lower (6%) than that of CA-Control 3 concrete and the compressive strength of CA-Pos. 12 and CA-Pos. 18 concretes was slightly higher (4.9%) than that of CA-Control 3 concrete. No specific trend was observed in the 28-day compressive strength test results by varying the gradation either beyond the control 1 or control 3.

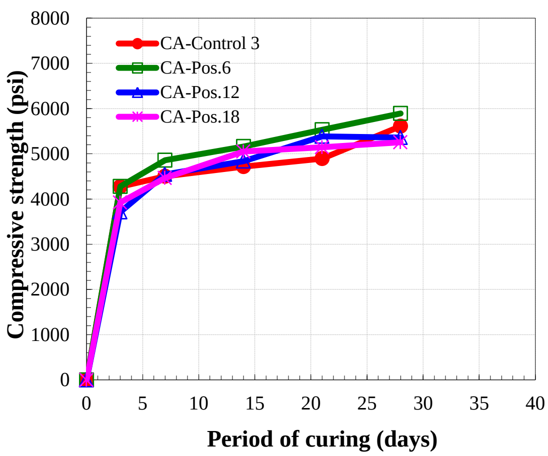
The rate of compressive strength development with concretes containing the 2nd set of aggregates as shown in Figure 14 (a) through (d) was similar to that of the 1st set of aggregates, i.e., there is only a slight variation in the early- and later-age strength development of concretes containing different coarse aggregate gradation. Here, the compressive strength of different concretes ranged from 6306 psi – 6668 psi. The compressive strengths of the concretes produced from 2nd set of aggregates were found to be significantly higher than that of the concretes produced from 1st set of aggregates perhaps due to the superior quality of the former compared to that of the latter.



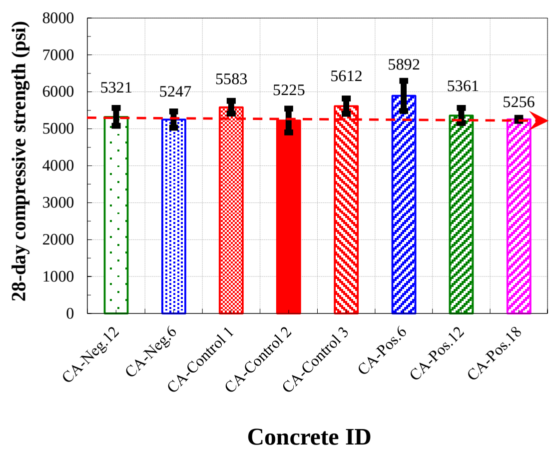
(a) Comparison of control concretes



(b) Comparison of control and negative failed gradation concretes

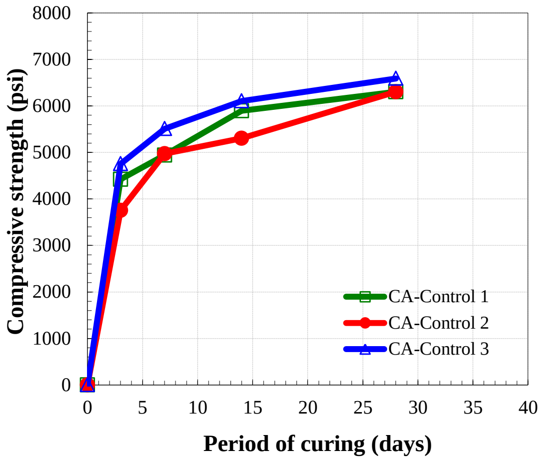


(c) Comparison of control and positive failed gradation concretes

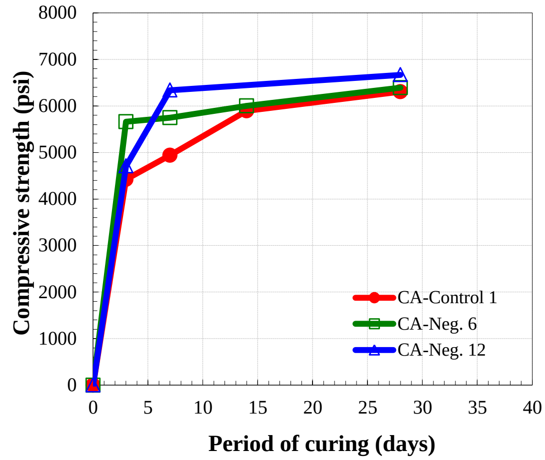


(d) Comparison of 28-day compressive strength of concretes

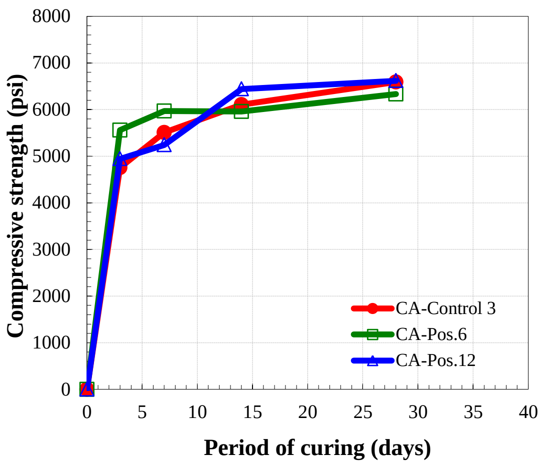
Figure 13. Effect of coarse aggregate gradation on the rate of compressive strength development of portland cement concrete containing 1st set of aggregates



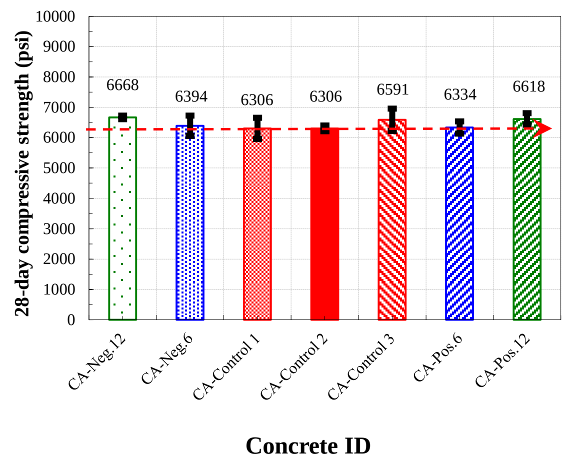
(a) Comparison of control concretes



(b) Comparison of control and negative failed gradation concretes



(c) Comparison of control and positive failed gradation concretes

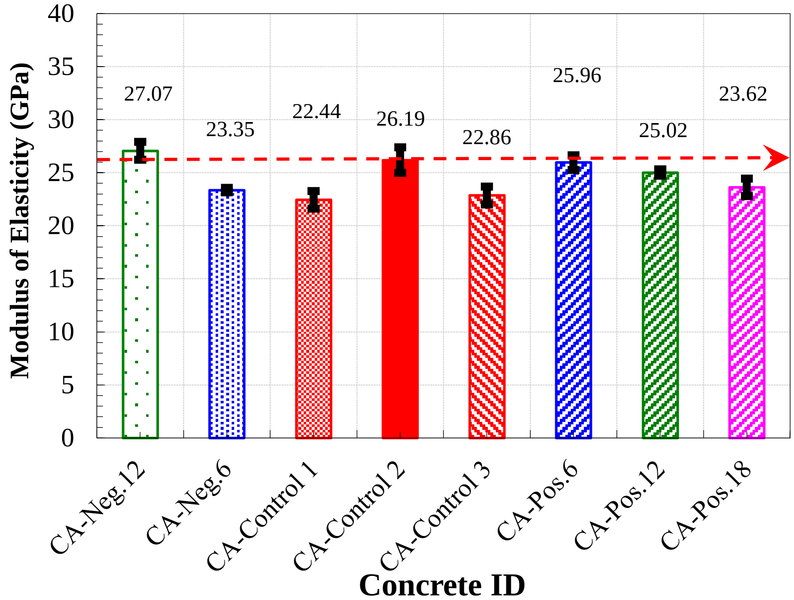


(d) Comparison of 28-day compressive strength of concretes

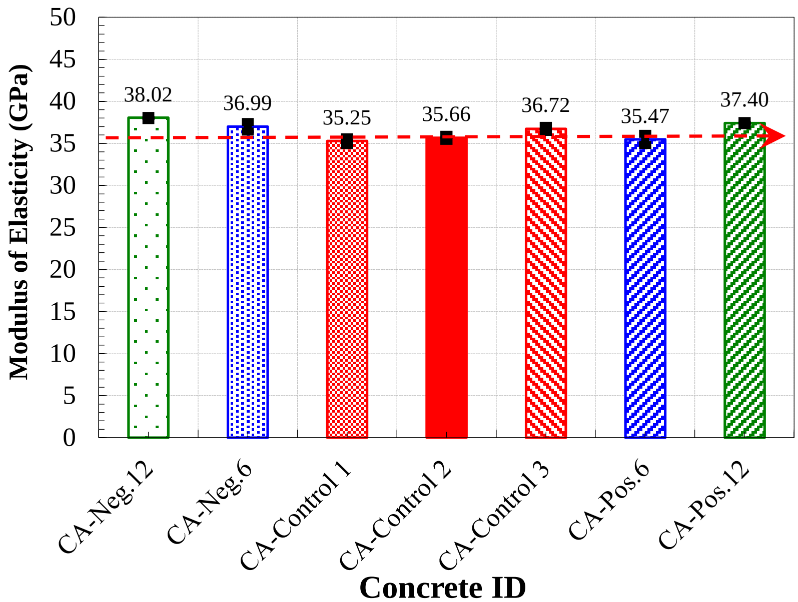
Figure 14. Effect of coarse aggregate gradation on the rate of compressive strength development of portland cement concrete containing 2nd set of aggregates

5.1.5 Modulus of elasticity

The effect of coarse aggregate gradation on the modulus of elasticity of concrete containing the 1st and 2nd set of aggregates is shown in Figures 15 (a) and 15 (b), respectively. With the 1st set of aggregates shown in Figure 15 (a), the modulus of elasticity (MOE) of CA-Control 2 concrete was found to be slightly higher or lower compared to other control concretes and those that contained failed coarse aggregate gradations. Within these control concretes, the MOE of CA-Control 1 and CA-Control 3 concretes was found to be lower than CA-Control 2 concrete by 14.32% and 12.71%, respectively, indicating that the deviation in the coarse aggregate gradation within the acceptable limits can somewhat decrease the MOE of control concretes. The MOE of concretes containing negatively and positively failed aggregate gradations was found to be slightly higher than that of their respective control concretes. Overall, there was a slight increasing trend observed with the MOE of concrete, as the coarse aggregate gradation falls out of specifications beyond CA-Control 1 and CA-Control 3 concretes. However, the MOE of concrete containing the extreme failed gradations (CA-Neg. 12 and CA-Pos. 12) was either slightly higher or lower than the CA-Control 2 concrete, indicating that the MOE of concrete is not much influenced by the changes in the coarse aggregate gradation. The results obtained with the 2st set of aggregates as shown in Figure 15 (b) is slightly different from that obtained with the 1st set of aggregates, i.e., the MOE of control and failed gradation concretes were more or less equal to each other. Though the results with 2nd set of aggregates were slightly different, the inference that the MOE of concrete is not much influenced by the changes in the coarse aggregate gradation as observed previously holds good here also. Perhaps, this is not surprising as the modulus of elasticity of concrete is a function of the volume content of its individual components and their density and bond characteristics between different components, rather than a direct function of the gradation of the individual particles. Considering also that the density, air content and yield of concrete across different concrete mixtures has virtually not been influenced by the gradation of the aggregate, the modulus of concrete is unlikely to be significantly influenced by the gradation of the aggregates in the concrete. These findings corroborate each other well.



(a) With first set of aggregates (aggregate 1 and sand 1)



(c) With second set of aggregates (aggregate 2 and sand 2)

Figure 15. Effect of coarse aggregate gradation on the modulus of elasticity of concrete

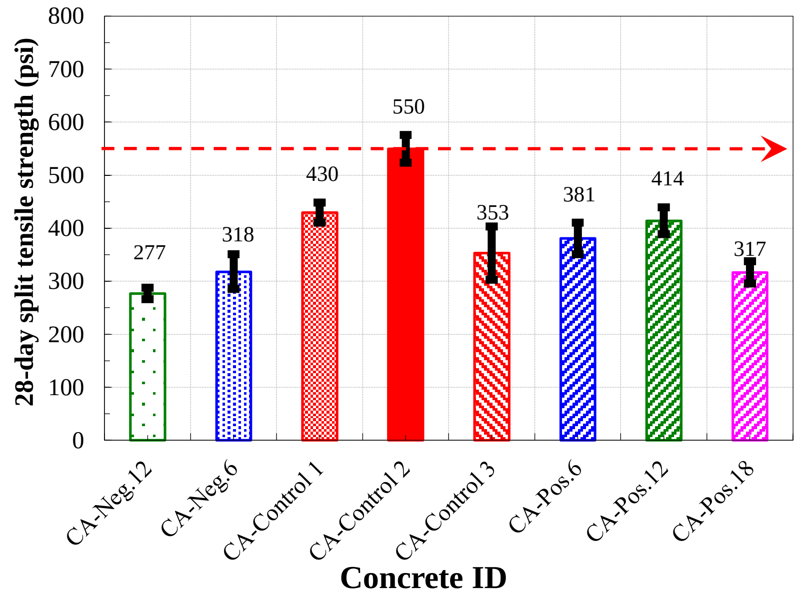
5.1.6 Split tensile strength

The effect of coarse aggregate gradation on the 28-day split tensile strength of concrete containing the 1st and 2nd set of aggregates is shown in Figures 16 (a) and 16 (b), respectively.

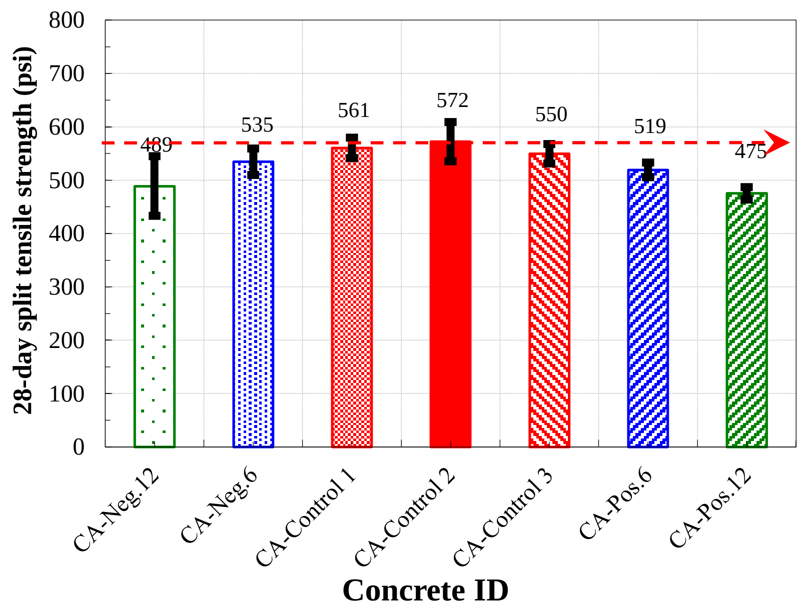
With the 1st set of aggregates shown in Figure 16 (a), the 28-day split tensile strength of CA-Control 2 concrete was found to be higher compared to other control concretes and those that contained failed coarse aggregate gradations. The split tensile strength of concrete containing Control 1, 2 and 3 coarse aggregate gradations was found to be 430 psi, 550 psi and 353 psi, respectively. Within these control concretes, the split tensile strength of CA-Control 1 and CA-Control 3 concretes was found to be lower than CA-Control 2 concrete by 21.81% and 35.82%, respectively, indicating that the deviation in the coarse aggregate gradation within the acceptable limits can significantly decrease the split tensile strength of control concretes. The split tensile strength of concretes containing negatively failed aggregate gradations (CA-Neg. 6 and CA-Neg. 12) was found to be 26%-35% lower than that of their control concrete (CA-Control 1). In the case of positively failed aggregate gradation, the CA-Pos. 6 and CA-Pos. 12 concretes registered split tensile strength slightly higher than the CA-Control 3, while the CA-Pos. 18 concrete registered split tensile strength slightly lower than the CA-Control 3 concrete. Overall, there was a decreasing trend observed with split tensile strength of concrete, as the coarse aggregate gradation tends to fall out of specifications, with the negatively failed aggregate gradation registering higher strength loss than the positively failed aggregate gradation.

With the 2nd set of aggregates as shown in Figure 16 (b), the 28-day split tensile strength of CA-Control 1 and CA-Control 3 concretes was found to be only slightly lower than that of the CA-Control 3 concrete, indicating that there is not much decrease in the split tensile strength of concrete, when the aggregate gradations are within the specifications. However as the coarse aggregate gradations was negatively or positively increased, there appears to be a decreasing trend in the split tensile strength of concrete. For example, the split tensile strength of CA-Neg. 12 and CA-Pos. 12 concrete significantly decreased when compared with CA-Control 1 and CA-Control 2 concretes.

The split tensile strength of concrete containing the 2nd set of aggregates was found to be higher than that of concrete containing the 1st set of aggregates perhaps due to the higher quality and cleanliness of the aggregate, in particular fine aggregate. It is important to note that the effect of aggregate gradation on the split tensile strength of concrete obtained with 1st and 2nd set of aggregates were approximately similar, with the 1st set of aggregates registering higher strength compared to the 2nd set of aggregates as the aggregate gradations deviate away from the acceptable limits in the specifications.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 16. Effect of coarse aggregate gradation on the split tensile strength of concrete

5.1.7 Hardened air content

The effect of coarse aggregate gradation on the hardened air content of concrete containing 1st and 2nd set of aggregates are shown in Table 15 and 16, respectively.

Table 15. Hardened air content and spacing factor of concrete containing 1st set of aggregates

Mixture ID	Air content	Spacing factor
	%	mm
CA-Neg. 12	4.05	0.230
CA-Neg. 6	5.05	0.189
CA-Control 1	4.18	0.25
CA-Control 2	3.41	0.242
CA-Control 3	3.24	0.266
CA-Pos. 6	3.99	0.325
CA-Pos. 12	3.49	0.250
CA-Pos. 18	3.63	0.314

Table 16. Hardened air content and spacing factor of concrete containing 2nd set of aggregates

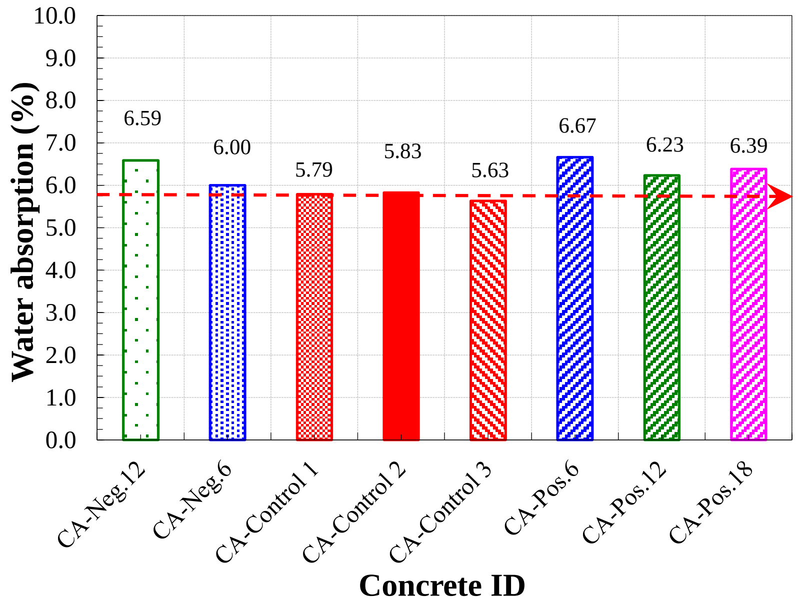
Mixture ID	Air content	Spacing factor
	%	mm
CA-Neg. 12	3.28	0.279
CA-Neg. 6	2.66	0.378
CA-Control 1	2.68	0.369
CA-Control 2	3.05	0.269
CA-Control 3	3.01	0.31
CA-Pos. 6	2.75	0.287
CA-Pos. 12	2.94	0.325

As shown in Table 15 with the first set of aggregates, the air content of concrete containing different coarse aggregate gradations were approximately equal to each other. The hardened air content of the control concretes was only slightly different from each other. In addition, the hardened air content of control and failed gradation concretes did not vary much and there is no specific trend observed as the coarse aggregate gradation deviated from that of their respective control gradations. The trends observed with the fresh air content of concrete containing the 1st set of aggregates was similar to that containing the 2nd set of aggregates as shown in Table 16, i.e., there is not significant variation in the fresh air content of concrete containing different aggregate gradation.

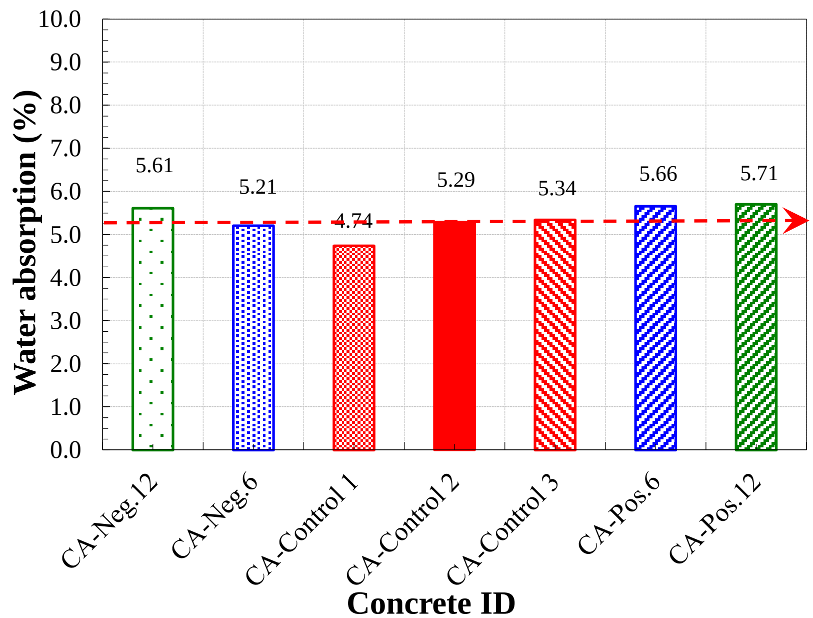
5.1.8 Water absorption

The effect of coarse aggregate gradation on the 28-day water absorption of concrete containing the 1st and 2nd set of aggregates is shown in Figures 17 (a) and 17 (b), respectively.

With the 1st set of aggregates shown in Figure 17 (a), the 28-day water absorption of CA-Control 2 concrete was found to be slightly higher compared to other control concretes. The water absorption of concretes containing negatively and positively failed aggregate gradations was found to be higher than that of their respective control concretes. There is a slight increase trend observed with the water absorption of concretes, as the coarse aggregate gradations falls out of specifications beyond CA-Control 1 concrete where as a specific increasing or decreasing trend with the water absorption of concretes was not noted as the coarse aggregate gradations falls out specification beyond CA-Control 3 concrete. The percentage increase in the water absorption values of the failed gradations, CA-Neg. 12 and CA-Pos. 18 concretes, is 13% and 10%, respectively, when compared to CA-Control 2 concrete. Similar results and inferences were also obtained with the second set of aggregates as shown in Figure 17 (b). Although the percentage increase in the water absorption values of concrete containing the failed gradations with respect to the control gradations is not large, the trends suggest that aggregates failing to meet the acceptable gradation specifications are likely to show higher water absorption and therefore consequently are at a slightly higher risk for potential durability problems.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 17. Effect of coarse aggregate gradation on the 28-day water absorption of concrete

5.1.9 Rapid chloride ion permeability test

The effect of coarse aggregate gradation on the rapid chloride ion permeability value (RCP) of concrete containing the 1st set of aggregates is shown in Figures 18. Due to equipment malfunction, the RCP tests could not be conducted on the 2nd set of aggregates.

With the 1st set of aggregates shown in Figure 18 (a), the RCP of all the concretes were well above 4000 Coulombs, indicating that all concretes are highly permeable. The RCP value of CA-Control 2 concrete was found to be slightly higher than that of CA-Control 3 concrete but lower than that of CA-Control 1 concrete. There is no substantial difference between the RCP values of the control concrete. However, in the case of concretes containing negatively or positively failed gradation, their RCP values were very high, significantly higher than their respectively control concretes (CA-Control 1 and CA-Control 3). For example, the RCP value of the failed gradations, CA-Neg. 12 and CA-Pos. 18 concretes are 51% and 121% higher than that of their respective control concretes. In addition, it can be observed that an increasing trend in the RCP value is observed, as the coarse aggregate gradation tends to fall beyond the gradations of CA-Control 1 and CA-Control 3 concretes. This implies that coarse aggregate gradation can significantly affect the permeability of concrete if the gradation exceeds beyond the acceptable limits.

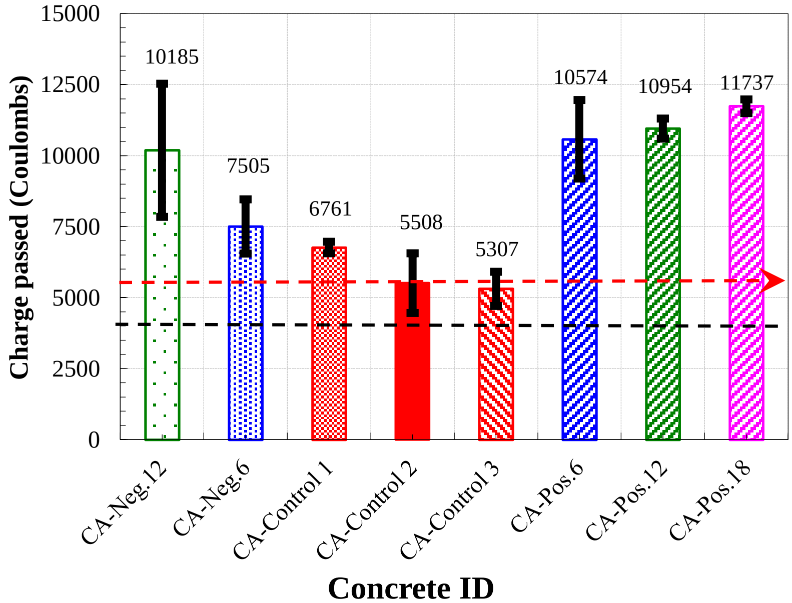
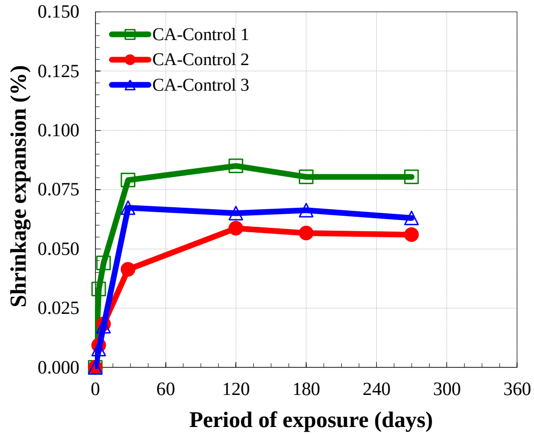


Figure 18. Effect of coarse aggregate gradation on the rapid chloride permeation ion value of concrete with first set of aggregates (aggregate 1 and sand 1)

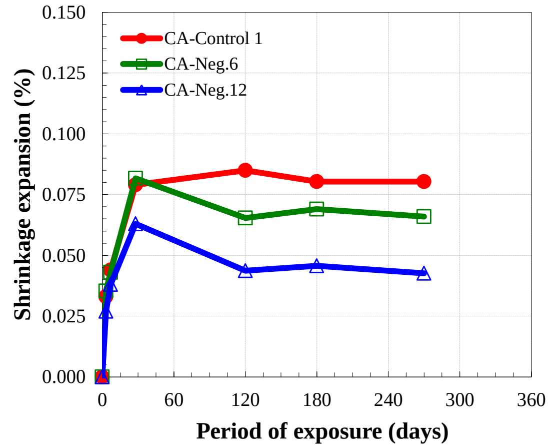
5.1.10 Drying shrinkage

The effect of coarse aggregate gradation on the drying shrinkage behavior of concrete containing the 1st set of aggregates is shown in Figure 19, respectively. As the Figures 19 (a) through (c) shows, the drying shrinkage of all concretes showed similar behavior, i.e., with an increase in the period of exposure from 0 to 270 days, the shrinkage increased as expected. However, a steep increase in the shrinkage of concretes was noticed only at early exposure periods from 0 to 28 days. The shrinkage tends to level off after 28 days and there is not much increase in the shrinkage at later ages.

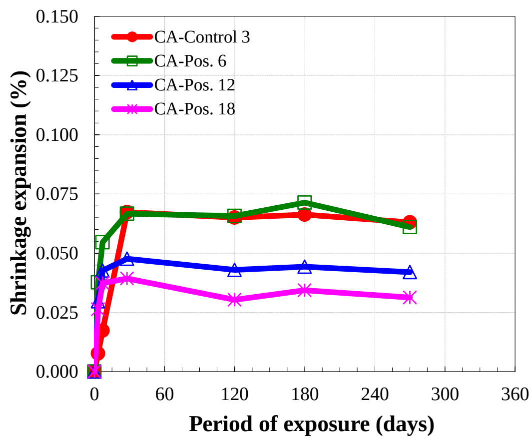
In order to obtain a comparative drying shrinkage performance of all concretes, the 180-day drying shrinkage of these concretes were compared as shown in Figure 19 (d). Within the control concretes, the 180-day shrinkage of CA-Control 1 and CA-Control 3 concretes were found to be higher than that of the CA-Control 2 by 40% and 16%, respectively. It appears that the selection of coarse aggregate gradation within the permissible limits can cause significant variation in the drying shrinkage of concretes. The 180-day shrinkage of concretes containing negatively and positively failed aggregate gradations was found to be lower than that of their control concretes (CA-Control 1 and CA-Control 3). Although there is a decreasing trend observed with the 180-day shrinkage of concretes as the coarse aggregate gradation deviate from the control 1 and control 3 gradations, trend does not appear to be significant as the shrinkage of concrete with the failed gradations (CA-Neg. 12 and CA-Pos. 18) is more of less equal to the shrinkage of the CA-Control 2 concrete.



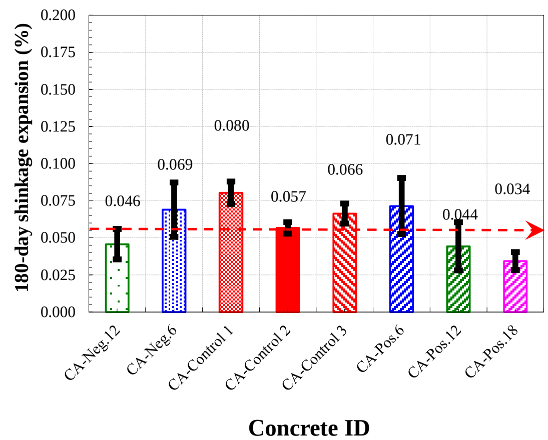
(a) Comparison of control concretes



(b) Comparison of control and negatively failed gradation concretes



(c) Comparison of control and positively failed gradation concretes



(d) Comparison of 180-day drying shrinkage expansions of different concretes

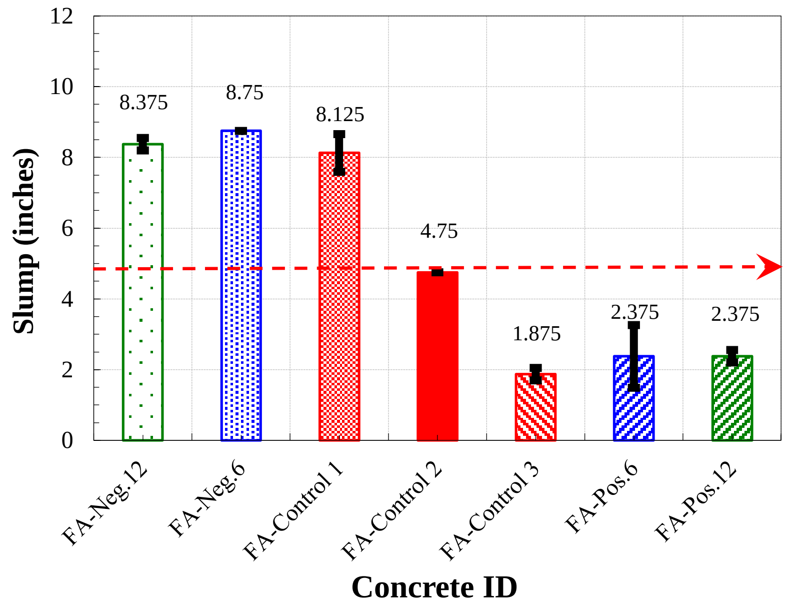
Figure 19. Effect of coarse aggregate gradation on the drying shrinkage behavior of portland cement concretes containing 1st set of aggregates

5.2 Effect of fine aggregate gradation on specific properties of concrete

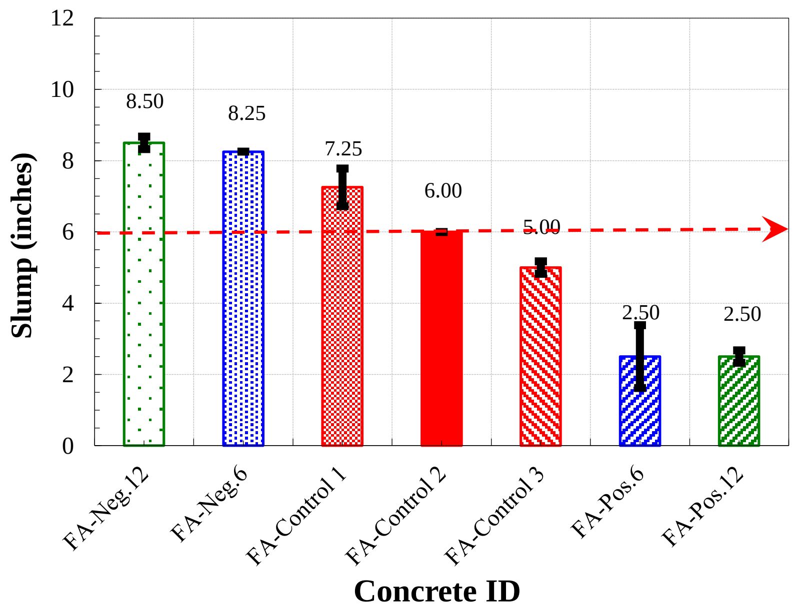
5.2.1 Slump

The effect of fine aggregate (FA) gradation on the slump of concrete containing the 1st and 2nd set of aggregates is shown in Figures 20 (a) and 20 (b), respectively.

With the 1st set of aggregates shown in Figure 20 (a), the slump of FA-Control 1 mixture was found to be 71% higher than that of FA-Control 2 mixture, while the slump of FA-Control 3 mixture was found to be 60% lower than that of FA-Control 2 mixture. There is a significant variation within the slump values of the control mixtures. The slump of concretes containing negatively and positively failed aggregate gradations was found to be slightly higher than that of their respective control concretes (FA-Control 1 and FA-Control 3) and there is no specific trend observed in the slump values by varying the gradation beyond the FA-Control 1 or FA-Control 3 up to FA-Neg. 12 or FA-Pos. 12. The trends observed in the slump values of concretes containing the 2st set of aggregates as shown in Figure 20 (b) was found to be almost similar to that obtained with the 1st set of aggregates, i.e., the slump of control concretes were significantly different, the slump of concretes containing negatively failed aggregate gradation (i.e. coarser sand) was slightly higher than the FA-Control 1 mixtures and there is no specific trend observed in the slump, by altering the aggregate gradations beyond the control gradation. In the case of positively failed aggregate gradation concretes (i.e. finer sand), the slump values were slightly lower than that of the FA-Control 3 mixtures. Overall, it can be inferred that the deviation in the fine aggregate gradation beyond the FA-Control 2 has a significant influence on the slump of concretes. These trends are in agreement with conventional wisdom on the influence of surface area of fine aggregate on the slump of the concrete.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

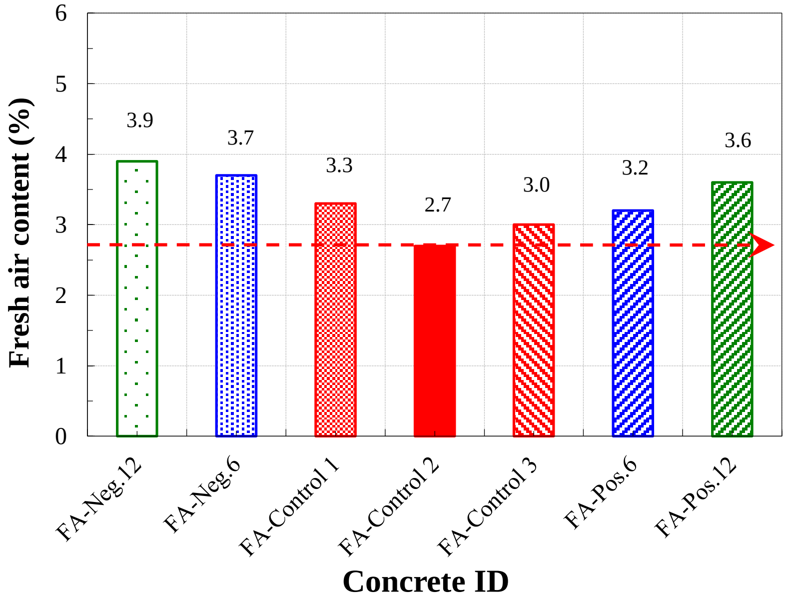
Figure 20. Effect of fine aggregate gradation on the slump of concrete produced from different sets of aggregates

5.2.2 Fresh air content

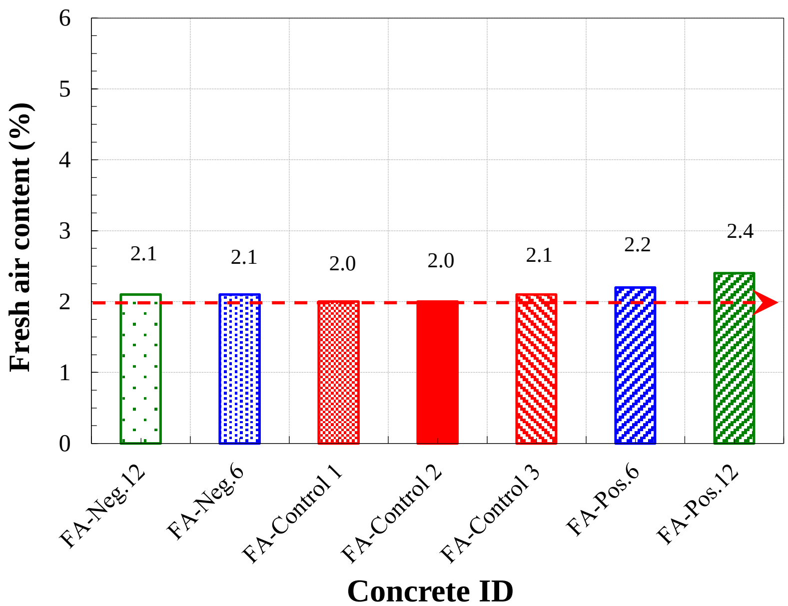
The effect of fine aggregate gradation on the fresh air content of concrete containing the 1st and 2nd set of aggregates is shown in Figures 21 (a) and 21 (b), respectively.

With the 1st set of aggregates shown in Figure 21 (a), the fresh air content of FA-Control 2 mixture was found to be slightly higher than that of the other control mixtures (FA-Control 1 and FA-Control 3), indicating that the change in the fine aggregate gradation within the control gradation has only minimal effects on the fresh air content of concrete. However, the fresh air content of concretes containing failed aggregate gradation was found to significantly higher from that of the respective control concretes. An increasing trend in the fresh air content of concrete was observed with an increase in the fine aggregate gradation beyond the control gradations. With the 2nd set of aggregates shown in Figure 21 (b), the fresh air content of the control concretes and all concretes containing negatively and positively failed aggregate gradation except FA-Pos. 12 were comparable. The fresh air content of FA-Pos. 12 was 20% higher than that of FA-Control 2. The trend observed with the fresh air content of concretes containing the 1st and 2nd set of aggregates very different probably due to the change in the quality of aggregates used.

Overall, it can be inferred that the variation in the aggregate gradation beyond a certain limit tend to significantly increase the fresh air content of concrete.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 21. Effect of fine aggregate gradation on the fresh air content of concrete produced from different sets of aggregates

5.2.3 Density and Yield

The effect of fine aggregate gradation on the density and yield of concrete containing 1st and 2nd set of aggregates are shown in Table 17 and 18, respectively.

Table 17. Density and yield of concrete containing 1st set of aggregates

Concrete ID	Density	Relative yield
	lb/ft^3	No unit
CA-Neg.12	144.13	0.988
CA-Neg.6	143.53	0.992
CA-Control 1	143.70	0.990
CA-Control 2	146.08	0.974
CA-Control 3	145.01	0.982
CA-Pos.6	144.14	0.987
CA-Pos.12	145.18	0.980

Table 18. Density and yield of concrete containing 2nd set of aggregates

Concrete ID	Density	Relative yield
	lb/ft^3	No unit
CA-Neg.12	147.90	0.962
CA-Neg.6	146.80	0.969
CA-Control 1	147.90	0.962
CA-Control 2	147.60	0.964
CA-Control 3	147.20	0.967
CA-Pos.6	147.10	0.968
CA-Pos.12	145.80	0.976

Data in Table 17 shows that with the first set of aggregates, the densities of concrete containing different coarse aggregate gradations were approximately equal to each other and there is no substantial variation in their densities. For example, the density of concrete containing the extreme gradations (FA-Neg. 12 and FA-Pos. 12) was found to be only 1.33% and 0.62% lower than that of the FA-Control 2 concrete, indicating that the deviation in the fine aggregate gradation, similar to coarse aggregate gradation, beyond the control gradations has very less influence on the density of concrete. In addition, the relative yield of all the concrete was also found to be approximately equal and no specific trend was observed with the relative yield. As expected, the yield and density of concrete corroborate each other.

The trends observed with the density of concrete containing the 2nd set of aggregates was similar to that of the 1st set of aggregates as shown in Table 18, i.e., the density of concrete containing different fine aggregate gradations were approximately equal. The yield of concrete also supports the density data, with less variation between each of the concrete mixtures.

5.2.4 Rate of compressive strength

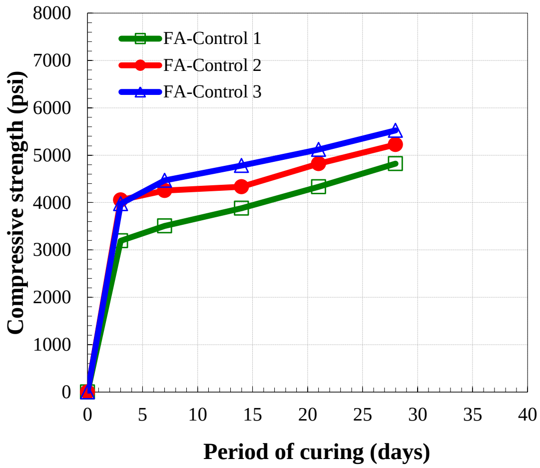
The effect of fine aggregate gradation on the rate of compressive strength development of concrete containing the 1st and 2nd set of aggregates is shown in Figure 22 and 23, respectively.

As shown in Figures 22 (a) through (c) with the 1st set of aggregates, there is a steep increase in the compressive strength of concretes at early curing periods (3- or 7-day), while there is only a slight increase in the compressive strength of concretes at later curing periods. The early-age compressive strength of FA-Control 2 concrete was slightly above and below that of FA-Control 1 and FA-Control 3 concretes, respectively, as shown in the Figure 22 (a). In the case of the negatively failed aggregate gradation mixtures as shown in Figure 22 (b), their early-age compressive strengths were higher than that of FA-Control 1 mixtures, indicating that the aggregate gradation beyond the standard specification can potentially affect the early-age compressive strength of concrete. However, such a conclusion was not observed with positively failed aggregate gradation mixtures. In this case, the early age compressive strength of failed gradation and control mixtures (FA-Pos. 6, FA-Pos. 12 and FA-Control 3) was found to be approximately equal as can be seen in Figure 22 (c). Thus, the effect of fine aggregate gradation may or may not affect the early-age compressive strength of concrete.

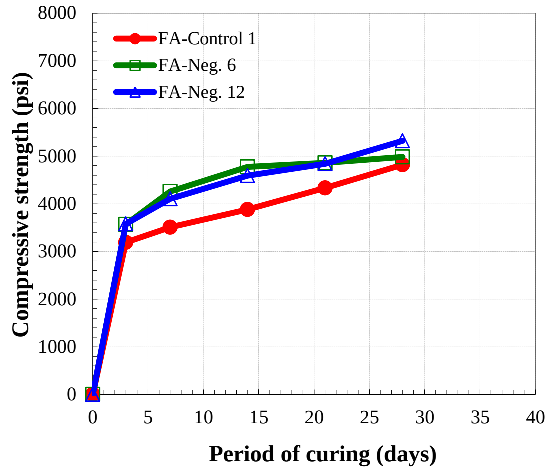
In order to understand the effect of fine aggregate gradation on the later-age compressive strength, a comparison of the 28-day compressive strength of all the concretes was performed as shown in Figure 22(d). As this figure shows, the compressive strength of different concretes ranged from 4820 – 5602 psi. Considering only the control concretes, the 28-day compressive strength of FA-Control 1 and FA-Control 3 concretes was found to be only 7.75% lower and 5.72% higher than that of FA-Control 2 concretes, indicating that the deviation in the fine aggregate gradation within the acceptable limits does not affect the 28-day compressive strength of concretes significantly.

The compressive strength of concretes containing negatively failed aggregate gradations was found to be slightly higher than that of their control concrete (FA-Control 1). In the case of positively failed aggregate gradation concretes, the compressive strength of FA-Pos. 6 concrete was slightly higher and that of FA-Pos. 12 was slightly lower than that of the FA-Control 3 concretes. No specific trend was observed in the 28-day compressive strength test results, up on varying the gradation either beyond the Control 1 and Control 3 fine aggregate gradations.

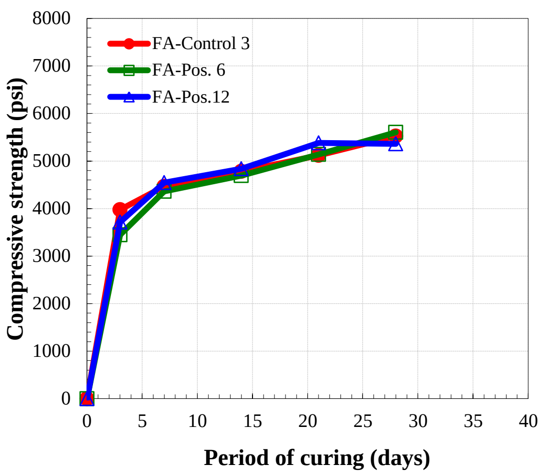
The rate of compressive strength development with concretes containing the 2nd set of aggregates as shown in Figure 23 (a) through (d) was similar to that of the 1st set of aggregates and that there is only a slight variation in the early and later age strength development of concretes containing different coarse aggregate gradation. Here, the compressive strength of different concretes ranged from 6130 – 6466 psi. The compressive strengths of the concretes produced from 2nd set of aggregates were found to be significantly higher than that of the concretes produced from 1st set of aggregates perhaps due to the superior quality of the former compared to that of the latter.



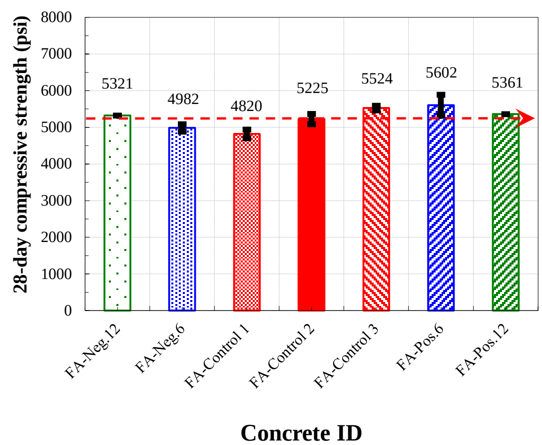
(a) Comparison of control concretes



(b) Comparison of control and negative failed gradation concretes

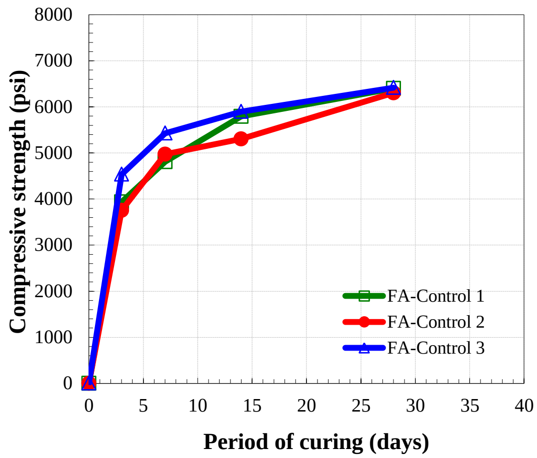


(c) Comparison of control and positive failed gradation concretes

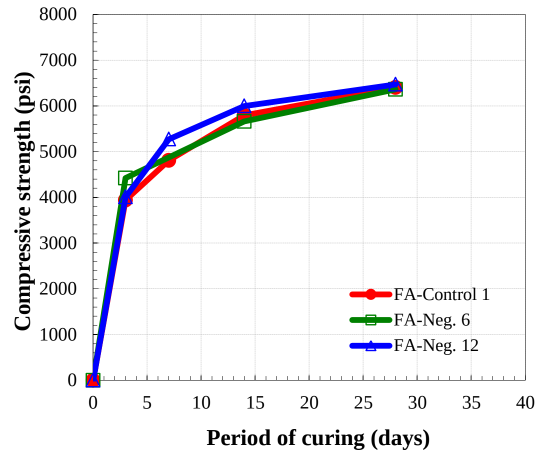


(d) Comparison of 28-day compressive strength of concretes

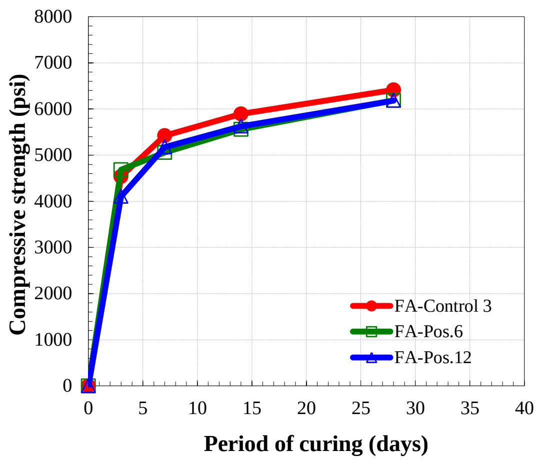
Figure 22. Effect of fine aggregate gradation on the rate of compressive strength development of portland cement concrete containing 1st set of aggregates



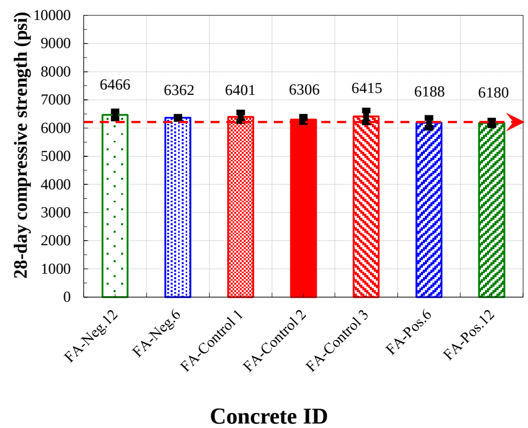
(a) Comparison of control concretes



(b) Comparison of control and negative failed gradation concretes



(c) Comparison of control and positive failed gradation concretes



(d) Comparison of 28-day compressive strength of concretes

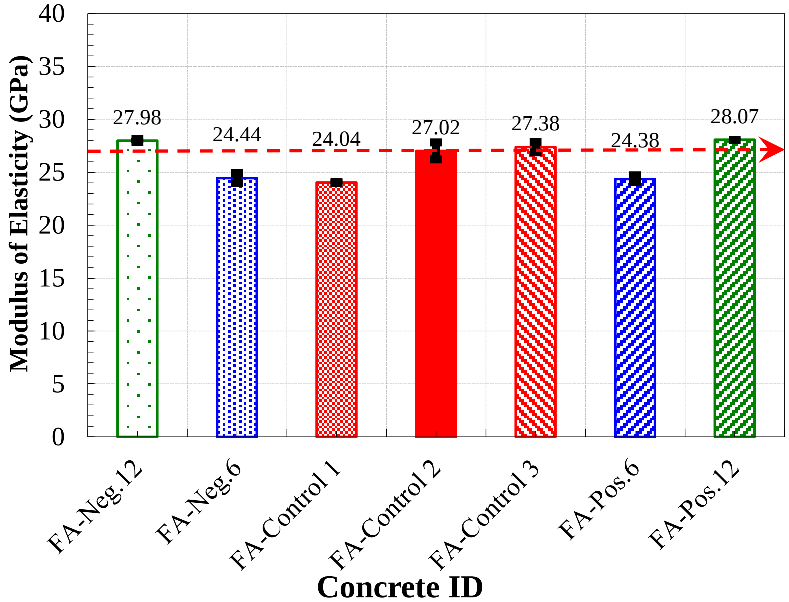
Figure 23. Effect of fine aggregate gradation on the rate of compressive strength development of portland cement concrete containing 2nd set of aggregates

5.2.5 Modulus of elasticity

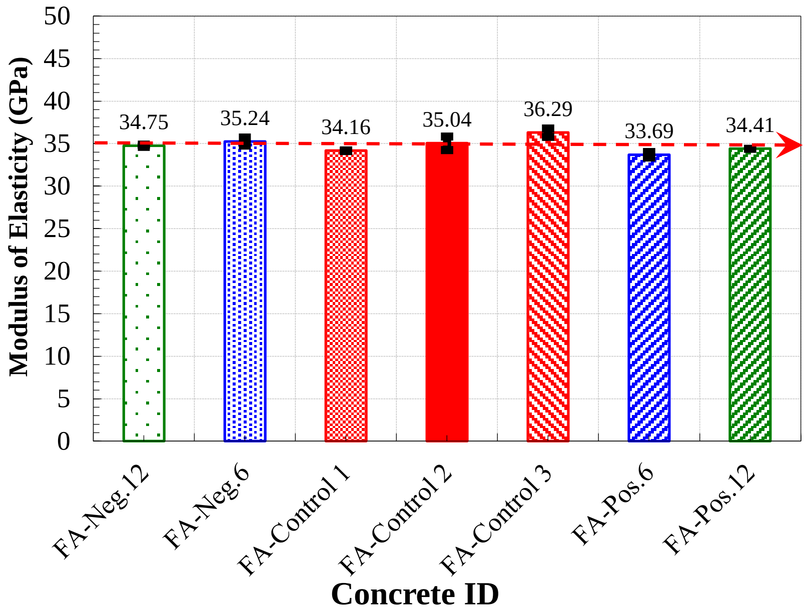
The effect of fine aggregate gradation on the modulus of elasticity of concrete (MOE) containing the 1st and 2nd set of aggregates is shown in Figures 24 (a) and 24 (b), respectively.

As the Figure 24 (a) shows, with the first set of aggregates, the MOE of FA-Control 1 and FA-Control 3 concretes was found to be only 11% lower and 1% higher than that of FA-Control 2 concrete, indicating that the deviation in the fine aggregate gradation within the acceptable limits does not significantly change the MOE of control concretes. The MOE of concretes containing negatively failed aggregate gradation was found to be higher than that of their control concrete. Though an increasing trend in the MOE of concrete was observed with a deviation in the fine aggregate gradation beyond FA-Control 1 concrete, the MOE of concrete containing failed aggregate gradation was approximately comparable to that of FA-Control 2 concrete. In the case of concrete containing positively failed fine aggregate gradation, no specific trends in the MOE was observed and the values was similar to that of FA-Control 2 and FA-Control 3 concretes. With the second set of aggregates as shown in the Figure 24 (b), the MOE of all the concretes were found to be more or less equal.

Thus, it can be inferred that the deviation in the fine aggregate gradation has less influence on the MOE of concrete.



(a) With first set of aggregates (aggregate 1 and sand 1)



(a) With second set of aggregates (aggregate 2 and sand 2)

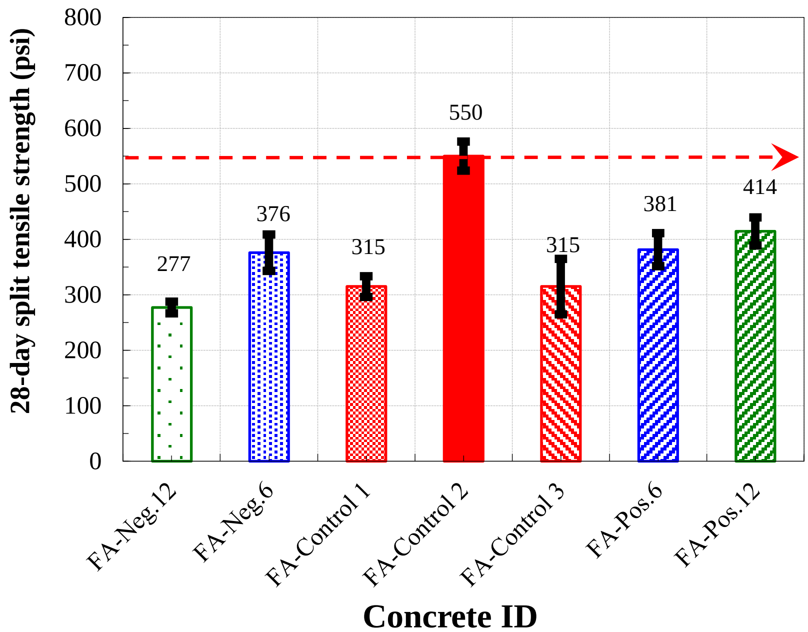
Figure 24. Effect of fine aggregate gradation on the modulus of elasticity of concrete

5.2.6 Split tensile strength

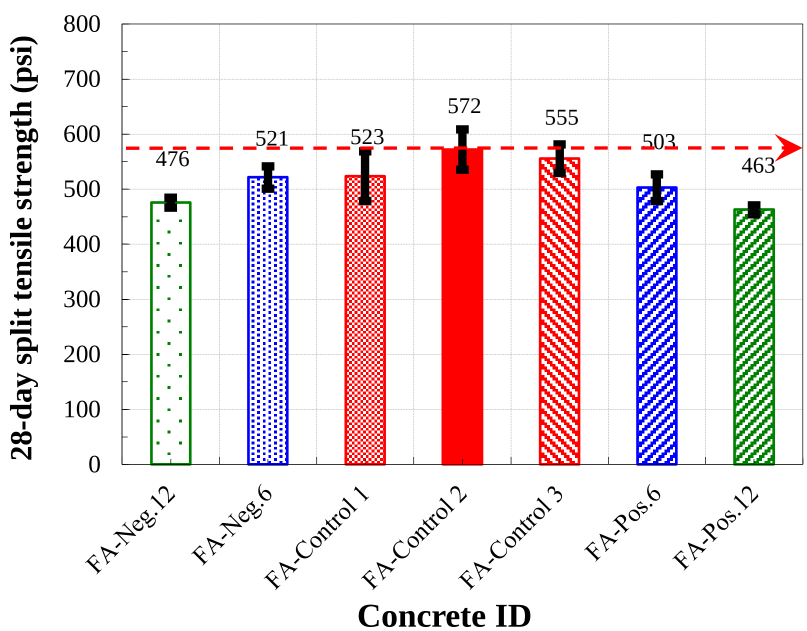
The effect of fine aggregate gradation on the 28-day split tensile strength of concrete containing the 1st and 2nd set of aggregates is shown in Figures 25 (a) and 25 (b), respectively.

As the Figure 25 (a) shows, with the 1st set of aggregates, the 28-day split tensile strength of FA-Control 2 concrete was found to be higher compared to other control concretes and those that contained failed coarse aggregate gradations. Within the control concretes, both the FA-Control 1 and FA-Control 3 concretes was found to be lower than FA-Control 2 concrete by 42%, indicating that the deviation in the fine aggregate gradation within the acceptable limits can significantly decrease the split tensile strength of concrete. The split tensile strength of concretes containing negatively failed aggregate gradation (FA-Neg. 6 and FA-Neg. 12) was found to be approximately equal to that of their control concrete (FA-Control 1). In the case of positively failed aggregate gradation, a slight increasing trend in the split tensile strength of concrete was observed, as the fine aggregate gradation deviated away from the control mixtures.

The trends observed with the split tensile strength of concrete containing the 2st set of aggregates was slightly different compared to that containing the 1st set of aggregates. Within the control concretes, the split tensile strength of FA-Control 1 and FA-Control 3 concretes were 8% and 3% lower than that of the FA-Control 2 concrete, indicating that fine aggregate deviation within the control gradation does not significantly alter the split tensile strength of concrete. In the case of negatively and positively failed gradation concretes, a definite decreasing trend in the split tensile strength was observed as the fine aggregate gradation deviated significantly from their respective control gradations.



(a) With first set of aggregates (aggregate 1 and sand 1)



(b) With second set of aggregates (aggregate 2 and sand 2)

Figure 25. Effect of fine aggregate gradation on the 28-day split tensile strength of concrete

5.2.7 Hardened air content

The effect of fine aggregate gradation on the hardened air content of concrete containing 1st and 2nd set of aggregates are shown in Table 19 and 20, respectively.

Table 19. Hardened air content and spacing factor of concrete containing 1st set of aggregates

Mixture ID	Air content	Spacing factor
	%	mm
CA-Neg. 12	4.92	0.222
CA-Neg. 6	4.52	0.218
CA-Control 1	4.13	0.236
CA-Control 2	3.41	0.242
CA-Control 3	4.32	0.282
CA-Pos. 6	4.46	0.252
CA-Pos. 12	4.52	0.229
CA-Pos. 18	4.92	0.222

Table 20. Hardened air content and spacing factor of concrete containing 2nd set of aggregates

Mixture ID	Air content	Spacing factor
	%	mm
CA-Neg. 12	3.12	0.308
CA-Neg. 6	2.85	0.336
CA-Control 1	3.13	0.319
CA-Control 2	3.05	0.269
CA-Control 3	3.14	0.321
CA-Pos. 6	2.93	0.276
CA-Pos. 12	3.09	0.261

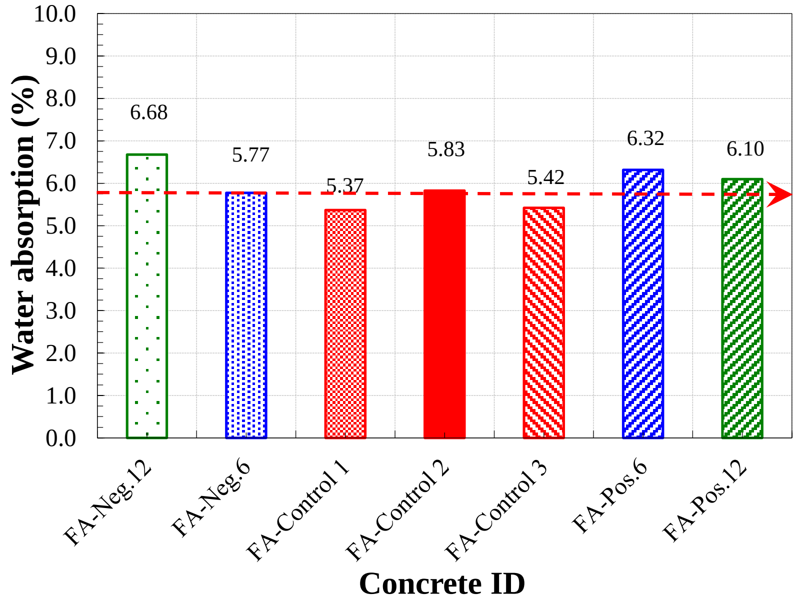
As the Table 19 shows, with the first set of aggregates, the air content of concrete containing different fine aggregate gradations were approximately equal. There is no substantial variation within the hardened air content of the control concretes. Similarly, the hardened air content of control and failed gradation concretes were approximately the same and there is no specific trend observed in the hardened air content of concrete, as the fine aggregate gradation deviated from their respective control gradations. The trends observed with the air content of concrete containing the 1st set of aggregates was similar to that containing the 2nd set of aggregates as shown in Table 20, i.e., there is not significant variation in the fresh air content of concrete containing different aggregate gradation. However, the hardened air content of concrete obtained with the 2nd set of aggregates was found to be slightly lower than that with the 1st set of aggregates probably due to the variation in the quality of fine and coarse aggregates used.

5.2.8 Water absorption

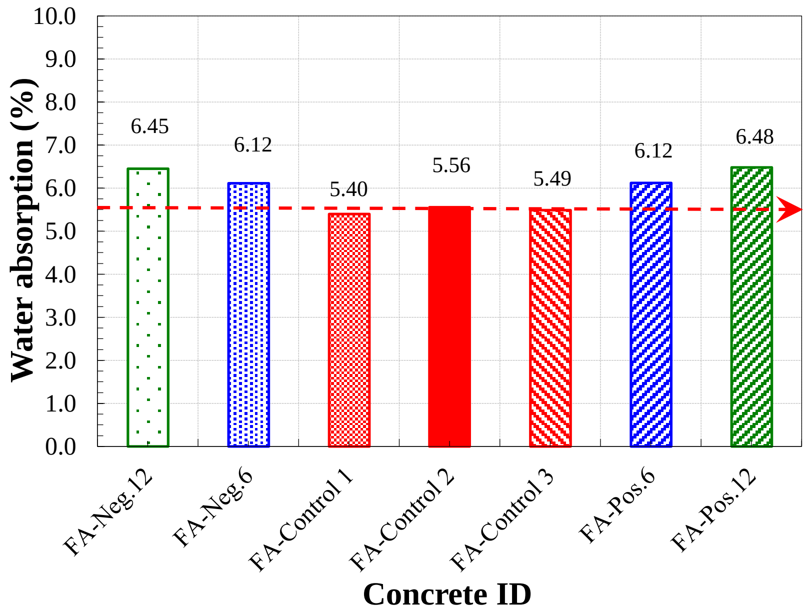
The effect of fine aggregate gradation on the 28-day water absorption of concrete containing the 1st and 2nd set of aggregates is shown in Figures 26 (a) and 26 (b), respectively.

As the Figure 26 (a) shows, with the 1st set of aggregates, the 28-day water absorption of the FA-Control 2 concrete was found to be slightly higher compared to other control concretes. The water absorption of concretes containing negatively failed aggregate gradation was found to be higher than that of FA-Control 1 concrete. For example, the water absorption of FA-Neg. 6 and FA-Neg. 12 concretes was higher by 7% and 24%, respectively, as the fine aggregate gradation deviated away from the Control 2 gradation. Similar observations were also seen with concretes containing positively failed aggregate gradations.

As shown in Figure 26 (b) with the second set of aggregates, the water absorption of control concretes was found to be approximately same. The water absorption of concretes containing negatively and positively failed aggregate gradations increased as the gradation deviated from their respective control gradations.



(a) With first set of aggregates (aggregate 1 and sand 1)

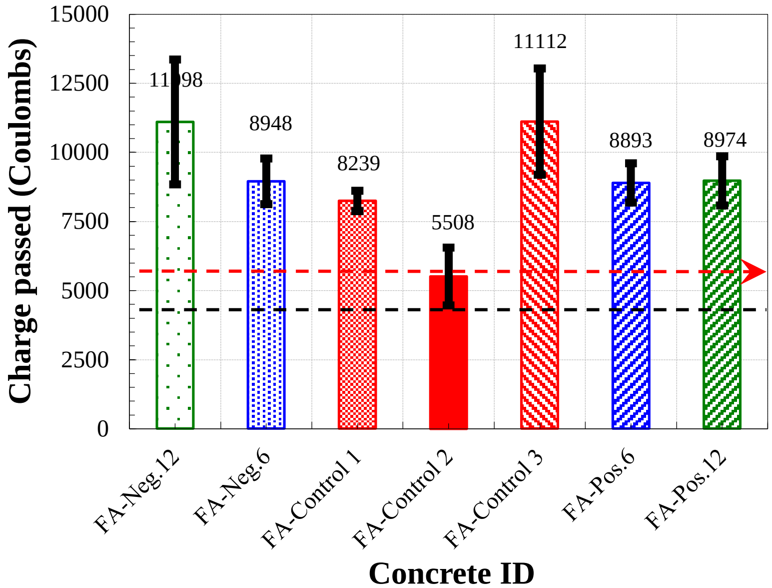


(b) With second set of aggregates (aggregate 2 and sand 2)

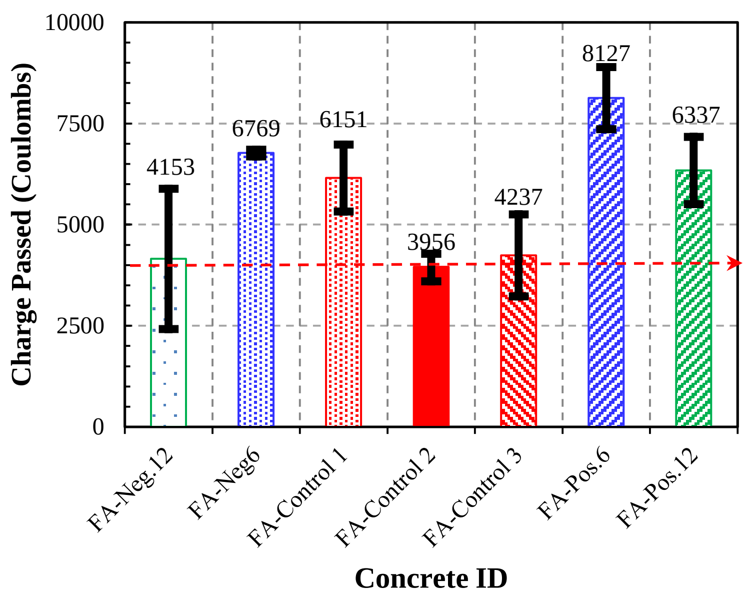
Figure 26. Effect of fine aggregate gradation on the 28-day water absorption of concrete

5.2.9 Rapid chloride ion permeability test

The effect of fine aggregate gradation on the rapid chloride ion permeability value (RCP) of concrete containing the 1st and 2nd set of aggregates is shown in Figures 27 (a) and (b), respectively. With the 1st set of aggregates shown in Figure 27 (a), the RCP of all the concretes were well above 4000 Coulombs, indicating that all concretes are highly permeable. The RCP value of FA-Control 1 and FA-Control 3 concretes was found to be 50% and 102% higher than that of FA-Control 2 concrete, indicating that the variation in the fine aggregate gradation within the control gradation has significant effect on the RCP value of concrete. In the case of concretes containing negatively failed aggregate gradation, the RPC values were found to be even higher than that of FA-Control 1 concrete. For example, the RCP value of concretes containing the negatively failed gradations (i.e. coarser sands), FA-Neg. 6 and FA-Neg. 12 concretes was found to be 8.60% and 42% higher than that of FA-Control 1 concrete. In addition, an increasing trend in the RCP value of concrete was also observed as the fine aggregate gradation deviated from the Control 1 gradation, indicating that there is a significant influence on the permeability of concrete. However, in the case of concretes containing positively failed aggregate gradation (i.e. finer sands), the RCP values were slightly lower than that of the FA-Control 3 concrete, indicating that the deviation in the fine aggregate gradation beyond Control 3 gradation has less effect on the RCP value of concrete. Similar trends were observed with 2nd set of aggregates as seen in Figure 27 (b). Compared to Control-2, all the other concrete RCP values were higher. However, no definite trend could be observed in concrete mixtures having aggregates with gradations beyond Control-1 and Control-3 gradations.



(a) With 1st Set of Aggregates (Coarse Aggregate 1 and Sand 1)



(b) With 2nd set of aggregates (Coarse aggregate 2 and sand 2)

Figure 27. Effect of fine aggregate gradation on the rapid chloride permeation ion value of concrete

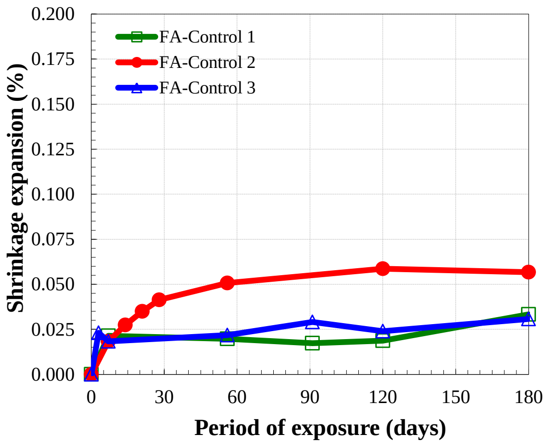
5.2.10 Drying shrinkage

The effect of fine aggregate gradation on the drying shrinkage behavior of concrete containing the 1st set of aggregates is shown in Figure 28. Drying shrinkage studies on the 2nd set of aggregates had to be abandoned due to failure of the environmental chamber in the midst of the test.

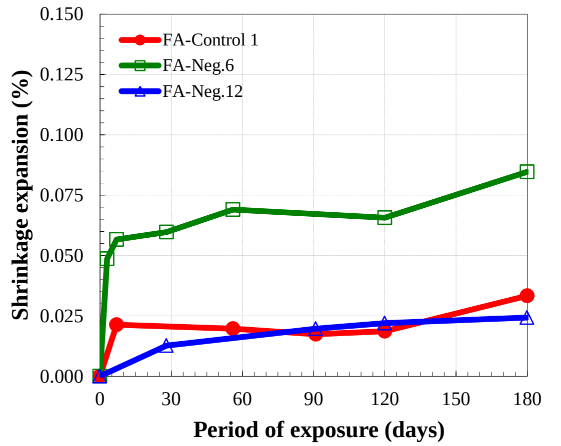
As the Figures 28 (a) through (c) shows, the drying shrinkage of all concretes showed similar behavior, i.e., with an increase in the period of exposure from 0 to 180 days, the shrinkage increased as expected. However, a steep increase in the shrinkage of concretes was noticed only at early exposure periods. The shrinkage tends to level off after a certain exposure period and there is no more increase in the shrinkage at later ages.

In order to obtain a comparative drying shrinkage performance of all concretes, the 180-day drying shrinkage was compared as shown in Figure 28 (d). Within the control concretes, the 180-day shrinkage of FA-Control 1 and FA-Control 3 concretes were found to be lower than that of the FA-Control 2 by 63% and 72%, respectively. It appears that the deviation in the fine aggregate gradation within the permissible limits (control gradation) can cause significant variation in the drying shrinkage of concrete.

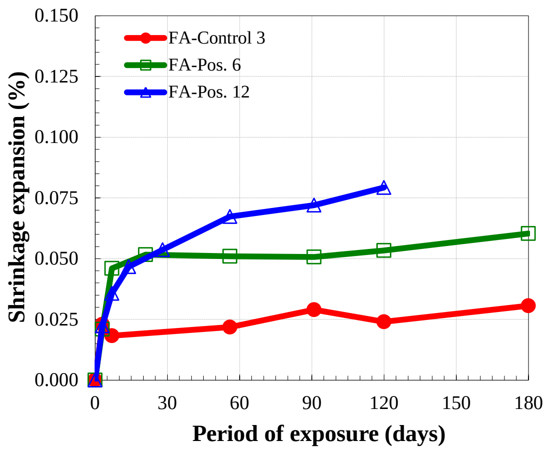
The 180-day shrinkage of concretes containing negatively and positively failed aggregate gradations was found to be higher than that of their control concretes (FA-Control 1 and FA-Control 3) but lower than that of FA-Control 2. There is no specific trend observed with the 180-day shrinkage of concretes, as the fine aggregate gradation deviated from the respective control gradations.



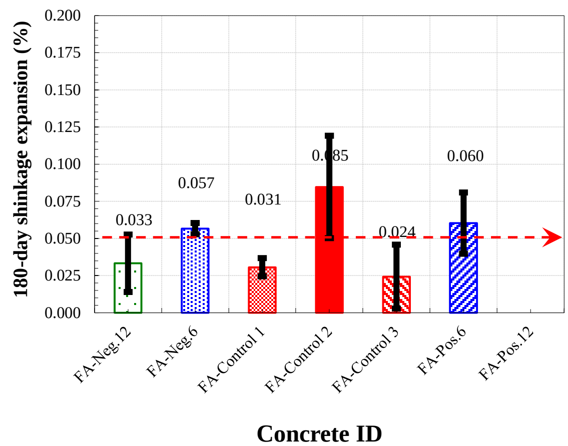
(a) Comparison of control concretes



(b) Comparison of control and negatively failed gradation concretes



(c) Comparison of control and positively failed gradation concretes



(d) Comparison of 180-day drying shrinkage expansions of different concretes

Figure 28. Effect of coarse aggregate gradation on the drying shrinkage behavior of portland cement concretes containing 1st set of aggregates

6.0 CONCLUSIONS

The principal objective of this research study was to investigate the impact of aggregate gradations that fail to meet the standard specifications on the fresh and hardened properties of concrete. Considering the large number of variables that can potentially impact the findings of this study, a careful selection of key parameters was made to isolate the effect of aggregate gradation on properties of concrete. These limitations are discussed in detail under the scope of the research study in the Introduction chapter.

Under these considerations, the broad conclusion that can be drawn from this study is as follows: aggregate gradations, whether coarse aggregates or fine aggregates, failing to meet the standard SCDOT specifications have a broad range of impacts on various properties of concrete, depending on a number of factors. The impact on concrete properties ranges from nothing significant on certain properties (such as compressive strength, modulus of elasticity, density and others) to significant on certain other selected properties such as split tensile strength and rapid chloride ion permeability among others. The specific impact of a failed aggregate gradation not only depends on whether the aggregates fail on the coarser or the finer side of the gradation but also on the extent of the failure away from the acceptable gradation limits. Further, the impact of a failed gradation on the concrete is very unique to specific properties of concrete. Also, failure of gradation in fine aggregates appears to have more detrimental effect on concrete properties than failure of coarse aggregate gradation. Of particular importance is the observation that even when aggregate gradations vary within the allowable specified limits of the gradations (in case of both coarse and fine aggregates), some properties of concrete such as split tensile strength, rapid chloride ion permeability are significantly affected, while certain other properties of concrete such as compressive strength and modulus of elasticity are not influenced. Details of the specific impacts of failures in coarse and fine aggregate gradations are presented below.

6.1. Effect of Failed Coarse Aggregate Gradation on Properties of Concrete

Failure in meeting the acceptable gradation limits on specific sieves of coarse aggregate, on both sides of the gradation curve, i.e. coarser and finer, has minimal to no impact on certain plastic properties of concrete such as fresh air content, unit weight and yield of concrete. With regards to consistency of concrete as measured by its slump, although some variability in measured slump was observed when aggregate gradation varied beyond the control gradations no definitive trends in the results could not be observed in the present study. The impact of failed coarse aggregate gradation on hardened properties of concrete such as compressive strength and modulus of elasticity of concrete was not significant within the range of gradations investigated in the present study. However, the split tensile strength was affected when aggregate gradation deviated away from the middle of the acceptable limits of coarse aggregate gradation. Similarly, rapid chloride ion permeability showed dependence on aggregate gradation. While this may not appear to be intuitively meaningful, it is likely that the significant deviation in aggregate gradation may enhance percolation effects due to increased inter-connected ITZ regions, consequently affecting the permeability. This behavior was observed on both sides of the control gradation curves. Further research is needed to confirm this finding. Similar trend as observed with RCP results, but perhaps not as strong of trend was seen in the absorption results of concrete as a function of coarse aggregate gradation. No definitive trends could be observed with drying shrinkage of concrete as a function of coarse aggregate gradation. Similar to the results from fresh air content measurements in concrete, no influence of coarse aggregate gradation was observed on the hardened air content of concrete. Overall, the change in the properties of concrete observed in the concrete when the aggregate gradation varied within the acceptable limits of gradation was observed to be as significant, if not more, than when the gradation varied outside the bounds of the acceptable gradation.

6.1. Effect of Failed Fine Aggregate Gradation on Properties of Concrete

Variations in fine aggregate gradations appeared to have more significant impact on selected properties of concrete than the corresponding variations in the coarse aggregate gradation. In particular, deviation in fine aggregate gradation had a marked influence on the slump of concrete. Concrete mixtures with fine aggregate gradations that were deficient on the finer fractions of the size (i.e. negatively failed) showed significantly greater slump than concrete with control fine aggregate gradation. Concrete mixtures with fine aggregate gradations that were too fine, or in other words that lacked coarser fractions showed significantly less slump than control gradations. These trends are in perfect agreement with the observation that finer gradations of aggregates tend to have a significantly larger surface area thus leading to a greater demand for water and cement paste. Based on these results, it appears that when the fine aggregate gradation varies away from the middle of the acceptable range of gradation (i.e. Control-2) significant changes in properties of concrete were observed. However, much of this observed change in properties of concrete was observed due to variations in gradations within the existing limits of gradation. Fine aggregate gradations that fell out of specification (i.e. beyond Control-1 and Control-3 gradations) showed additional change in properties of concrete, but the magnitude of change beyond Control-1 and Control-3 was not much more. The air content of fresh concrete mixtures containing failed aggregate gradations showed slightly higher values than concrete mixtures containing control fine aggregate gradations, although the differences in the unit weight of concrete was minimal. Similarly, failed fine aggregate gradations had a negative impact on the split tensile strength and rapid chloride ion permeability of concrete compared to Control-2 gradation. Similar negative impact, but less significant than that observed in RCP results, was also seen in the water-absorption of concrete mixtures containing failed fine aggregate gradations. No significant effect was observed with drying shrinkage in concrete mixtures containing failed fine aggregate gradations.

7.0 RECOMMENDATIONS

Existing specifications on gradations for coarse and fine aggregate are very generous in allowing a wide variety of aggregate gradations as acceptable gradations. The changes in concrete properties associated with changes in gradations of aggregate, even within the acceptable limits, are rather large. Use of aggregate gradations, that fall out of specification within a range of ± 12% of the cumulative percent passing from the boundaries of acceptable gradation, did cause significant deviations in properties of concrete compared to an ideal gradation that is exactly in the middle of the specification band. However, compared to aggregate gradations that embrace the limits of the existing specifications, the use of failed gradations did not produce concrete that is significantly different. The precise impact of changes in aggregate gradation on concrete behavior is very specific to specific property of concrete as well as to failure on specific sieves and the magnitude of the failure in gradation. Considering these findings, it is recommended that the impact of failure of aggregate gradations be weighed considering the sensitivity of the specific structure for which the aggregate is to be used, and the potential impact of properties of concrete such as the split tensile strength and rapid chloride permeability have on the structural integrity and durability of the structure. In particular, the failed gradations should be compared to performance of concrete containing the aggregate that is barely acceptable based on the boundaries of existing specifications. Overall, failure in gradations of fine aggregates appears to have more detrimental impact on concrete properties than failure of gradation in coarse aggregates. It should also be noted that the current study was intended to be an exploratory study to determine the broad effects of failed aggregate gradations on the properties of concrete. To develop a more comprehensive knowledge on the impact of failed gradations of aggregate on concrete, it is recommended that further research be carried out employing realistic concrete materials, including manufactured sands, and typical field mixture proportions along with the typically used mineral and chemical admixtures. For instance, future studies should include manufactured sands, supplementary cementing materials such as fly ashes, slags and lower w/c ratio concretes than that was used in the current study. Also, the impact of blended aggregates (manufactured and natural sand combinations) should be considered in future investigations.

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