PROPORTIONING MANUFACTURED SAND IN FLOWABLE CONCRETE

By

RIYADH TURKI M ALTURKI

Bachelor of Science in Civil Engineering
King Saud University
Riyadh, Saudi Arabia
2012

Master of Science in Civil Engineering
Oklahoma State University
Stillwater, Oklahoma
2016

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2020

PROPORTIONING MANUFACTURED SAND IN

FLOWABLE CONCRETE

Dissertation Approved:

Dr. Tyler Ley

Dissertation Adviser

Dr. Bruce W. Russell

Dr. Norb Delatte

Dr. Ahmed Ismail

ACKNOWLEDGEMENTS

The author would like to acknowledge the Dolese Company for funding this research, and the Saudi Arabia Cultural Mission for sponsoring me. Also, I would like to acknowledge the Saudi Arabia Cultural Mission for Sponsoring me to acquire my degree. Conducting this research required an enormous skilled team for testing the concrete, therefore, I am so thankful to be working with undergraduates and graduates who were hardworking and intellectual.

Name: RIYADH TURKI M ALTURKI

Date of Degree: DECEMBER, 2020

Title of Study: PROPORTIONING MANUFACTURED SAND IN FLOWABLE CONCRETE

Major Field: CIVIL ENGINERING

Abstract: Manufactured sand has started to be used in concrete due to its availability and low cost. However, it has different shape properties, gradations, and mineralogy in comparison to the natural sand, and these differences can impact the performance of the concrete. This work quantifies the shape properties of manufactured sands and natural sands using sophisticated tests such as the AIMS II and more practical lab tests such as the Uncompacted Voids Content (ASTM C1257 -Method A). A correlation between these two measurements is presented. Next, concrete mixtures are proportioned with different amounts and gradations of manufactured sand at a variety of paste volumes, and their influence on the concrete workability is measured. Adjustments are also made to the Tarantula Curve Mixture Design tool to accommodate the different characteristics of manufactured sands in a concrete mixture for flowable concrete that must be finished. Further, this work investigates the impacts of manufactured sand on the pumping pressures. The workability and pumping pressure for three different manufactured sand sources and one natural sand are compared. Recommendations are made for the usage of manufactured sand in pumpable concrete mixtures. Also, the fine sand content and the combined uncompacted voids content of blended fine aggregates (natural sand and manufactured sand) are shown to be significant for concrete pumpability. Further, suggested changes are made to the fine sand content minimum limit on the Tarantula Curve to be 27% to keep pumping pressures manageable.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

1.0 Introduction

Concrete consists of cement, water, and aggregates, and it is the second most used commodity in the world besides water. About 70% of the volume of concrete is aggregate and so this creates a massive consumption of these materials [1]. While coarse aggregates used in concrete are mostly processed in quarries, the fine aggregates are commonly taken from natural sources such as river banks. According to the U.S. Geological Survey (USGS), approximately 1.33 billion metric tons of stones were crushed during 2017 to produce coarse aggregates for the concrete industry. Also, on average, 1.39 million metric tons of aggregates are produced per year to satisfy the need for aggregate in the construction industry [2]. This caused the waste product (manufactured sand) from crushing stones to produce coarse aggregates to increase by having enormous piles of manufactured sand accumulating and taking valuable space in quarries. Also, good quality natural fine aggregate (natural sand) sources are not widely available in some areas. This requires higher transportation costs to bring higher quality natural sands to the desired construction location [3]. These obstacles have led to finding an approach to balance the massive consumption of natural sand and the significant accumulation of manufactured sand in quarries. Therefore, the use of manufactured sand in concrete as a partial or full replacement of the natural sand has started to be common [3, 4, 5].

1.1 Manufactured sands in concrete

Using the manufactured sand in concrete applications can be advantageous in the aspects of minimizing the environmental issues, improving the concrete sustainability, and the economic cost. Also, incorporating the manufactured sand in concrete can improve the compressive strength and durability of concrete [3, 5, 6].

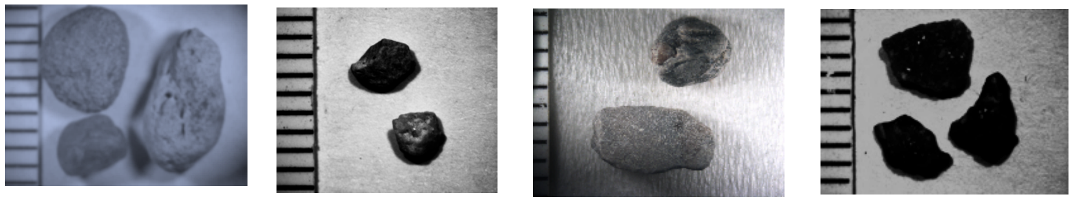
In concrete pavements, mineralogy and hardness of fine aggregate is important factor in obtaining good surface friction [7]. Skid-resistance of concrete pavements is impacted by the type of fine aggregates where high carbonated materials, such as manufactured sand, tend to be less polish resistance than siliceous materials, such as natural sand. Pavements with an increase in surface polishing tend to have low skid-resistance. Thus, it is typically in the concrete pavement mixtures to have the fine aggregate to be a blend of manufactured sand and natural sand [7]. Field and laboratory tests showed that high skid-resistance values can be achieved by blending manufactured sand with natural sand [8]. In terms of the response to vibration, concrete pavement mixtures with manufactured sand was found to respond similarly as the mixtures with natural sand. Concrete mixtures with manufactured sand essentially have similar creep and shrinkage as in mixtures with natural sand only [9]. A study has shown that blending manufactured sand with natural sand can improve the resistance to salt scaling in pavement concrete mixtures [9].

In flowable concrete mixtures, manufactured sand can be used as another source of fine aggregate. A study has shown that substituting 60% of natural sand with manufactured sand can be achieved while maintaining satisfactory workability and compressive strength [5]. Also, it was shown that partial replacement of natural sand with manufactured sand helped to minimize the surface cracking because of the lower coefficient of thermal expansion (CTE) that the manufactured sand has as opposed to the siliceous river sands [4, 10,11]. Johansen et al. concluded that the presence of manufactured sand particles decreased bleeding and increased shearing resistance in concrete [12].

Manufactured sand acquires mineralogical properties from the parent rock such as limestone, tuff, granite, basalt and quartzite. A study used a variety of manufactured sand sources from different parent rocks to prepare box girder concrete mixtures for high-speed railway and evaluate the workability, mechanical properties, durability and volume stability of these mixtures. This study showed that there were some differences in the workability due to the differences in the mineralogical properties and similar workability could be obtained by changing the admixtures dosages. The mechanical properties of mixtures with manufactured sand such as compressive strength, bending strength, and elasticity modulus were primarily related to the crushing index of manufactured sand. This study showed that the mineralogy of manufactured sand had slight influence on the chloride ion permeability resistance as well as the frost resistance. Concrete mixtures with different manufactured sand from different parent rock provided similar dry shrinkage performance [13].

Pumping manufactured sand concretes is susceptible to plugging due to the shape and gradation of manufactured sand [14.15]. However, a proper usage of the mineral and chemical admixtures can produce pumpable manufactured sand concrete. The fluidity of manufactured sand concrete after pumping showed a certain amount of loss where lower slump values were obtained. The loss in the slump was attributed to the Dissolution of the air bubbles due to the pumping pressure [16].

Typically, the manufactured sands have coarse gradations as opposed to natural sands, meaning that the materials retained on the coarse sand sieve sizes (No. 8 (2.36 mm) to No. 30 (600μm)) are higher than the materials retained on the fine sand sieve sizes (No. 30 (600μm) to No. 200 (75μm)). This coarser gradation of the manufactured sands can help in providing an aggregate size that is not found in both coarse aggregates and natural sands. This means that it can be used to improve packing and reduce voids. Fig. 1-1 shows manufactured sand and natural sand particles.



(a) (b) (c) (d)

Figure 1- 1 compares (a) natural sand (NS1), (b) manufactured sand (MS2), (c) manufactured sand (MS3), and (d) manufactured sand (MS7).

1.2 Challenges with manufactured sands in concrete

The gradations of manufactured sand are often undesirable for many concrete applications, and they vary from one source to another depending on factors such as the mineralogy of the source, the crusher type, the screening process, the washing method, and the gradation requirements of aggregate products [17, 18]. Also, these manufactured sand gradations rarely meet with the fine aggregate specifications of ASTM C33 [19]. Fig. 1-2 shows gradations of different manufactured sand sources plotted against the specified limits by the ASTM C33.

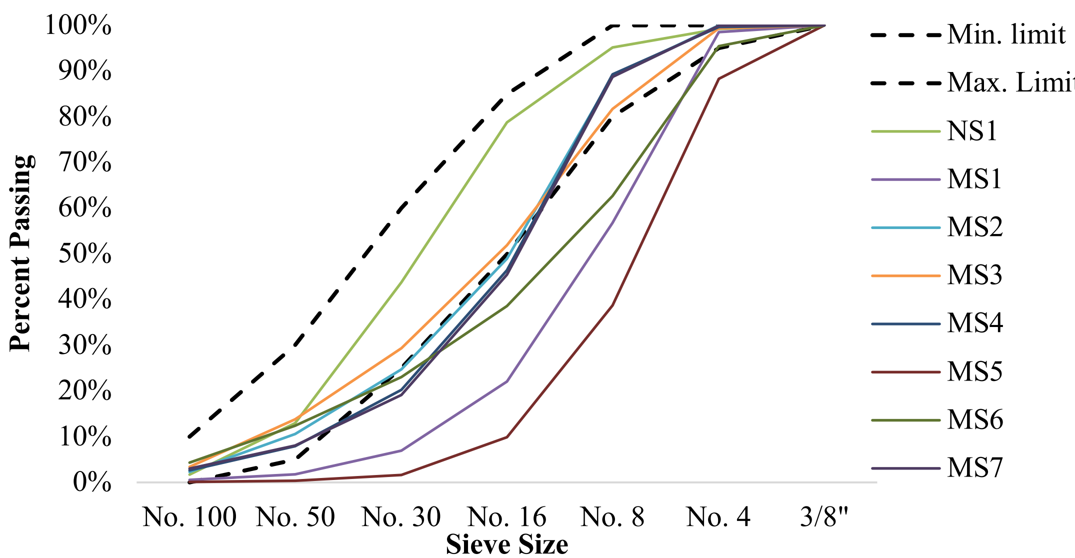


Figure 1- 2 illustrates the gradation limits of ASTM C33 for fine aggregate and typical gradations for manufactured sands.

The manufactured sand may contain high amounts of fines or particles that pass the No.200 (75µm) sieve, as shown in Fig. 1-3. These fines are especially problematic if the manufactured sands are not adequately washed. A high percentage of fines may cause an increase in the surface area of the aggregate particles, which can impact the water demand required to obtain constant workability [20, 21]. The manufactured sands are typically more angular than natural sand particles. Angular particles also tend to increase the water demand as they affect the voids content and frictional properties in concrete [22]. In summary, manufactured sands provide challenges in their gradation, fines, and higher angularity. For all of these reasons, manufactured sands can reduce the workability performance of concrete.

Figure 1- 3 shows an example of fines materials retained on a pan

1.3 Proportioning with the Tarantula Curve

It is desirable to have a concrete mixture design method that can produce successful mixtures and achieve the required fresh and hardened concrete properties. It is also desirable to have a design method that allows proportioning several aggregate sources to make a well combined aggregate gradation.

Conventional concrete mixture design methods only use natural sands that comply with the ASTM C33 requirements and have good shape properties. Recall that the manufactured has angular and texture particles, and typically does not meet the ASTM C 33 specifications. Hence, using convectional concrete mixture design methods to proportion manufactured sand in a mixture may not lead to achieving the desired fresh and hardened concrete properties. For example, using the ACI 211 [23] mixture design to design concrete mixtures containing manufactured sand frequently resulted in undesirable workability, segregation, excessive bleeding, and edge slumping [4, 24]. ACI 211 was designed for well graded aggregates that comply with the ASTM C33 requirements; also, for natural sand with smooth and rounded particles. Studies have revealed that the shape, texture, and combined aggregate gradation are the key factors that impact the concrete workability performance [25, 26, 27]. These factors are not entirely considered when selecting the amount of binder and the water content in a mixture when using the ACI 211 method. For instance, only the size, shape, and texture of coarse aggregate is accounted for by using the dry rodded unit weight, and the water content in a mixture is adjusted based on the shape (rounded VS angular) of coarse aggregates. However, studies have shown that the shape and texture of the fine aggregates have significantly more impact on the concrete workability in comparison to the coarse aggregates [26]. Shilstone showed that gap-graded combined gradations could be obtained by using the ACI 211 method [28]. This type of gradation requires higher volumes of a paste than well-graded gradations to obtain the same workability performance [12, 29, 30].

A better proportioning technique for manufactured sands needs to be developed. The combined aggregate gradation technique called the Tarantula Curve [31] has been successfully used to proportion a variety of aggregates together. Also, field mixtures made by contractors from various locations were analyzed by the Tarantula Curve, where aggregate gradations of the mixtures that were successfully made, placed, and utilized in different projects were compatible with the Tarantula Curve limits [6].

The International Roughness Index (IRI) measures the roughness of pavement surfaces where lower IRI values indicate smooth pavement surfaces; it was found that as the gradations of field pavement mixtures were within the Tarantula Curve, those pavements had lower IRI values [6].

The Tarantula curve can use two or more aggregate bins to proportion the aggregate into a combined gradation based on three key parameters: the sieve limits, the coarse sand volume, and the fine sand volume. The sieve limits provide maximum and minimum boundaries for designing a combined aggregates gradation and give explanations when those boundaries are not satisfied. Fig. 1-4 shows the Tarantula Curve specifications for aggregate proportioning.

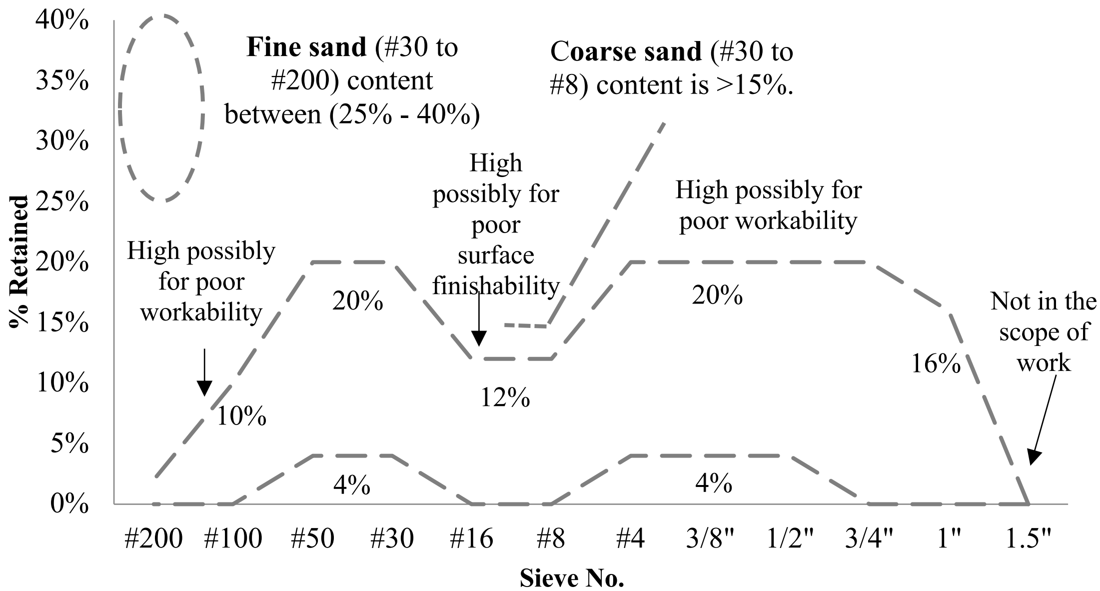


Figure 1- 4 shows the Tarantula Curve limits for both the sieve sizes and the fine sand and coarse sand volumes.

1.3.1 Coarse sand

The coarse sand volume is a key parameter of the Tarantula Curve. When the coarse sand volume is too low in a combined gradation, segregation and/or edge slumping has a high chance of occurring. The Tarantula Curve specified the coarse sand content should be greater than 15% to ensure that a mixture would have adequate cohesive properties. The coarse sand is the sum of materials retained on the sieve sizes from No.8 (2.36 mm) to No.30 (600µm). It can be calculated via the equation below:

$$\textbf{Coarse sand } (\#8\text{-}\#30) = \mathbf{P}_{\#8} + \mathbf{P}_{\#16} + \mathbf{P}_{\#30} \qquad \textbf{(eq. 1)}$$

Where,

$P_{\#8}$: the percentage of materials retained on the sieve size No. 8,

$P_{\#16}$: the percentage of the materials retained on the sieve size No 16,

$P_{\#30}$: the percentage of materials retained on the sieve size No 30.

1.3.2 Fine sand

The last key parameter of the Tarantula Curve has been the fine sand volume. This impacts the concrete workability performance as follows: excessive fine sand volume can cause a mixture to be stiff and sticky. In contrast, low fine sand volume affects the cohesiveness and finishability of a concrete mixture. The fine sand is the sum of the materials retained on the sieve sizes from No. 30 (600µm) to No. 200 (75 µm). It can be calculated via the following equation:

$$\textbf{Fine sand}\ (\#30\text{-}\#200) = \mathbf{P}_{\#30} + \mathbf{P}_{\#50} + \mathbf{P}_{\#100} + \mathbf{P}_{\#200} \qquad \textbf{(eq. 2)}$$

Where,

$P_{\#30}$: the percentage of materials retained on the sieve size No. 30

$P_{\#50}$: the percentage of the materials retained on the sieve size No 50

$P_{\#100}$: the percentage of materials retained on the sieve size No 100

$P_{\#200}$: the percentage of materials retained on the sieve size No 200

1.4 Focus of Investigation

This work aims to better understand the workability of concrete mixtures that contain manufactured sand and provide practical approaches to designing a concrete mixture with manufactured sand. The work will first quantify the shape properties of the manufactured sand. Next, guidelines will be provided to successfully proportion manufactured sand along with the other aggregates in a mixture that needs to be hand placed and finished, and still maintain acceptable workability and finishability suitable for flatwork applications. Also, this design procedure will allow concrete producers to have a choice of deciding the amount of manufactured sand based on the selection on the paste volume level. Further, recommendations will be given to be able to design concrete mixtures containing manufactured that need to be transferred via pumping equipment. This research presents the following chapters:

- **Chapter 2:** Proportion Manufactured Sand in Concrete for Workability and Finishability
- **Chapter 3:** Effect of Paste Content on Proportioning Concrete Mixtures with Manufactured Sands
- **Chapter 4:** The Impacts of Manufactured Sand on Pumping Concrete
- **Chapter 5:** Conclusion

CHAPTER II

PROPORTION MANUFACTURED SAND IN CONCRETE FOR WORKABILITY AND FINISHABILITY

2.0 Introduction

The use of manufactured sands, a man-made fine aggregate product from crusher fines, as a partial replacement or 100% replacement of fine natural aggregate (natural sand) in a concrete mixture has become more common [3, 5, 21]. Unfortunately, there can be challenges using manufactured sands in concrete mixtures as they can reduce the workability, and there is little published guidance on how to design concrete mixtures to use this material.

The advantage of the utilization of manufactured sand in concrete is the use of this waste product, and so it has a reduced cost compared to natural sands. Besides, the availability of natural sands is decreasing in some areas, which can require natural sand to be brought in from a significant distance, and this will in turn increase the cost of the concrete. Typically, manufactured sands will have a coarser gradation in comparison to the natural sand, which could help provide an aggregate size that is not found in coarse aggregates and natural sand. By using manufactured sand in concrete, this can improve the workability, strength, economy and also utilize a vital waste product.

Manufactured sands may contain higher amounts of fines or particles that pass the No.200 sieve size, especially if not adequately washed. A high percentage of fines could cause an increase in the surface area of the aggregate particles, which can impact the water demand required to obtain constant workability. Similarly, the concrete workability performance could be impacted if the materials retained on the No. 200 sieve are high [20, 21, 31]. Therefore, it is essential to know the amount of the fines of the manufactured sands before using them in concrete.

Like any other aggregate source, the gradation of manufactured sands changes from one source to another depending on the mineralogy of the source, the crusher type, the screening process, washing method, and gradation requirements of aggregate products [17, 18]. The shape and angularity of manufactured sand are a concern with many users since the particles are more angular than natural sand. These differences in shape and angularity properties can have an impact on the fresh concrete properties such as the workability, and the hardened concrete properties such as the compressive strength.

To overcome these workability challenges, it is often necessary to add more paste (binder and water) to the mixture. This increase in the paste can decrease any savings in the economy and sustainability for the concrete mixture. The concrete industry would benefit from a mixture design procedure to proportion concrete mixtures with manufactured sands. These mixtures with the manufactured sand can be used for flatwork construction, which is a common term used to describe a flat construction component such as slabs, sidewalks, and parking lots. This work aims to provide a practical and straightforward approach to designing concrete mixtures that need to be hand placed and finished with manufactured sand.

2.1 The Tarantula Curve

The Tarantula Curve is a practical aggregate proportioning technique for concrete that has shown success in guiding the production of workable concrete mixtures [31, 32]. The Tarantula Curve is shown in Fig. 2-1. A significant benefit of the Tarantula Curve is that it provides a comprehensive approach to designing the entire aggregate gradation, and it has specific recommendations for different size ranges of sand.

The coarse sand content, the sum of the materials retained on the sieve sizes from No.8 (2.36 mm) to No.30 (600µm), contributes to the cohesive properties of a concrete mixture. The fine sand content, the sum of the materials retained on the sieves sizes from No. 30 (600µm) to No. 200 (75 µm), impacts the workability performance in which an excessive fine sand content leads to high stiffness and stickiness. In contrast, low fine sand content affects the cohesiveness and finishability of concrete.

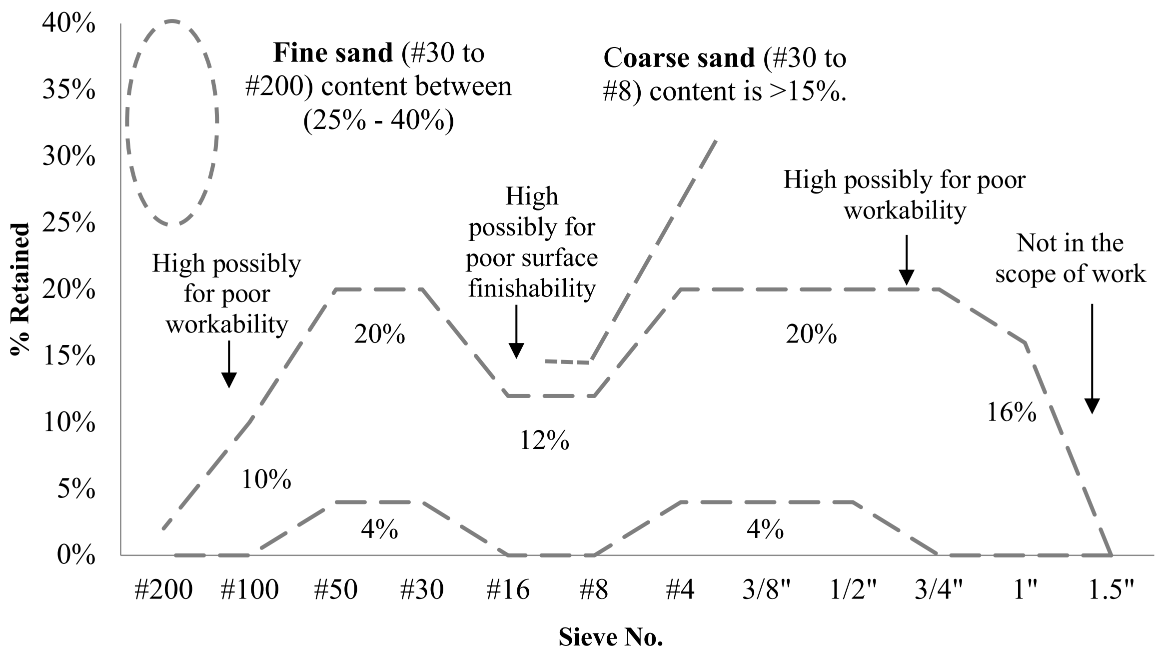


Figure 2- 1 shows the Tarantula Curve limits for both the sieve sizes and the fine sand and coarse sand volumes. (Modified from Cook [32])

2.2 Goal of the investigation

The goal of this work is to investigate the performance of manufactured sands in concrete that needs to be hand placed and finished. The angularity of the manufactured sands will be measured, and then each incorporated into the concrete to determine how angularity impacts the workability of the concrete mixture. Next, the workability performance of the resulting concrete mixtures will be investigated, and modified limits will be proposed for the Tarantula Curve.

2.3 Experimental methods

2.3.1 Materials

The concrete mixtures made for this study were prepared using Type I Portland cement conforming to ASTM C150 [33] with a 20% replacement by weight of a Class C fly ash meeting ASTM C618 [34]. The oxide analysis for the cementitious materials is reported in Table 2-1. The mid-range water reducer (WR) was a lignosulfonate meeting the Type A/F classification as per ASTM C494 [35].

Table 2- 1. Chemical Composition of the Cementitious Materials

Chemical Components	Type I (by mass %)	Fly ash Class C (by mass %)
SiO_2	21.1	16.95
CaO	62.1	40.98
Al_2O_3	4.7	17.22
MgO	2.4	10.28
Fe_2O_3	2.6	7.4
SO_3	3.2	2.41
K_2O	0.3	0.17
Na_2O	0.2	1.13
C_2S	17.8	--
C_3S	56.7	--
C_3A	8.2	--
C_4AF	7.8	--

The coarse and intermediate aggregate used in this study was from a single crushed limestone source. The coarse aggregate was a #57 meeting the ASTM C33 [19] with a nominal maximum aggregate size of 3/4 in. (19 mm), and the intermediate gradation had a 3/8 in. (9.5 mm) nominal maximum aggregate size. Two natural sand sources and nine manufactured sand sources were investigated in this study. Note that the manufactured sands used in this study were washed, which means that the contents of the fines were < 7%, conforming to the ASTM C 33. In this work, the fines ranged between 3.17%, 0.70%. Fig. 2-2 displays the aggregate gradation in individual percent retained according to ASTM C 136 [36]. Table 2-2 shows the properties of the fine aggregate.

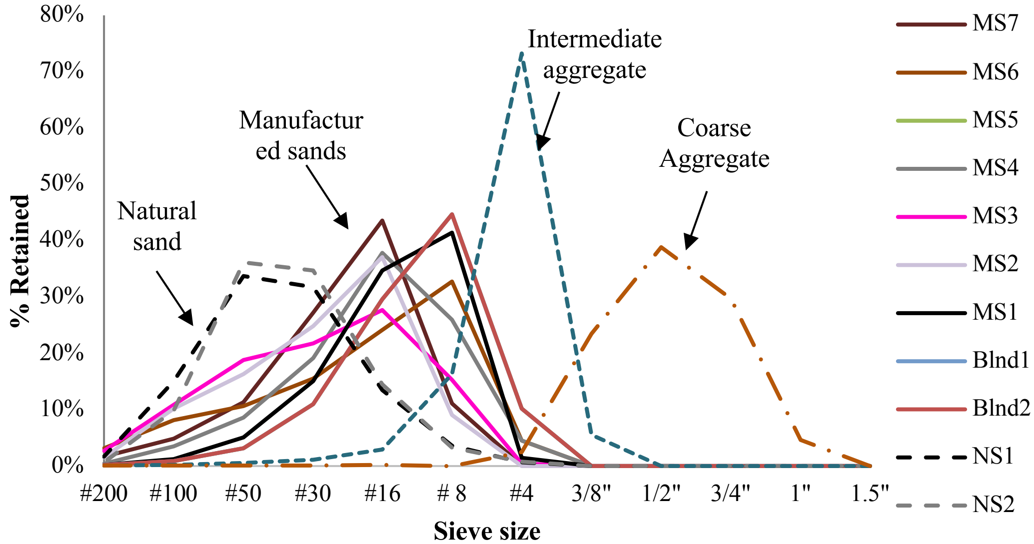


Figure 2- 2 shows the particle distribution of aggregates.

Table 2- 2. Fine Aggregates Information

Sand Type	Fine Aggregate	Fineness modulus	Specific gravity	No. 200 (%)	Fines (%)	Geology		
						Formation	Period	Rock Type
Natural sand (NS)	NS1	2.68	2.61	3.25	0.80	Terrace Deposits	--	Silica, Quartz
Manufactured sand (MS)	NS1*	4.43	2.61	0.20	0.70	Terrace Deposits	--	Silica, Quartz
	NS2*	2.78	2.63	0.2	0.70	Terrace Deposits	--	Silica, Quartz
	MS1*	4.13	2.67	0.20	0.70	Cool Creek and McKenzie	Ordovician	Limestone- clast conglomerates
	MS2	3.06	2.65	1.19	2.10	Chico Ridge	Pennsylvanian	Limestone-Biosparite
	MS3	3.12	2.66	3.17	3.85	Chico Ridge	Pennsylvanian	Limestone-Biosparite
	MS4	4.26	2.63	1.27	2.59	Grindstone Creek	Pennsylvanian	Limestone-Biosparite
	MS5*	4.43	2.75	0.20	0.70	West spring creek and Kindblade	Ordovician	Limestone-fossiliferous Igneous lime stone
	MS6	3.63	2.77	3.12	1.19	Raggedy Mountain	Early Cambrian	Gabbro-igneous rock
	MS7	3.36	2.76	1.70	1.63	Honey Creek	Ordovician	Dolomitic siltstone, Reagan Sandstone, and glauconitic sandstone
	MS7*	4.43	2.76	0.20	0.70	Honey Creek	Ordovician	Dolomitic siltstone, Reagan Sandstone, and glauconitic sandstone
Blended sand (Blend)	Blend 1*	4.43	2.71	0.20	0.70	Mixture of NS1 and MS5		
	Blend 2*	4.43	2.68	0.20	0.70	Mixture of NS1 and MS5		

Note that (*) means that the sand source has a fixed gradation.

2.3.2 Shape properties of manufactured sand

2.3.2.1 Micrograph images

Images of fine aggregate particles were taken to compare the angularity of the particle between different sources. A microscope device with a mounted camera was used to capture zoomed images to facilitate the observation, as shown in Fig. 2-3. Particles from each fine aggregate source were washed and dried before testing. Then, they were sieved into individual sieve sizes from sieve size No. 8 (2.36 mm) to No. 50 (300 μm). Seven particles from each sieve size were randomly selected to make up twenty-one particles for each sand source. This would allow enough particles to be tested from each sieve size and get an insight into the shape of the particles. The particles were put under the microscope to capture magnified images. The number of particles shown depended on the particle size and magnification. These images are useful to give an overview of the shape of the manufactured sand particles from different sources and sizes. A classification-criteria was used as described in Lindholm where five categories of angularity were used to describe the particle shape along with their intervals as the following: Well-rounded (5-6), Rounded (4-5), Sub-rounded (3-4), Sub-angular (2-3), Angular (1-2), and Very-angularity (0-1). Then, by using a statistical method called chi-square, a shape category was selected for a sand source from the visual images [37].

The number of particles for each group was counted, and this is known as the Frequency (F). The midpoint (M) for each category is the midpoint of each interval; for example, the midpoint of the well-rounded group is 5.5. Then, the following equation was used to calculate the mean roundness of a sand source [37].

$$\textbf{Mean Roundness} = (\Sigma(F\times M))/(\Sigma F) \qquad \textbf{(eq. 3)}$$

After determining the mean roundness value, it was converted back into the following angularity scale range: Well-rounded (5-6), Rounded (4-5), Sub-rounded (3-4), Sub-angular (2-3), Angular (1-2), and Very-angularity (0-1) [37].

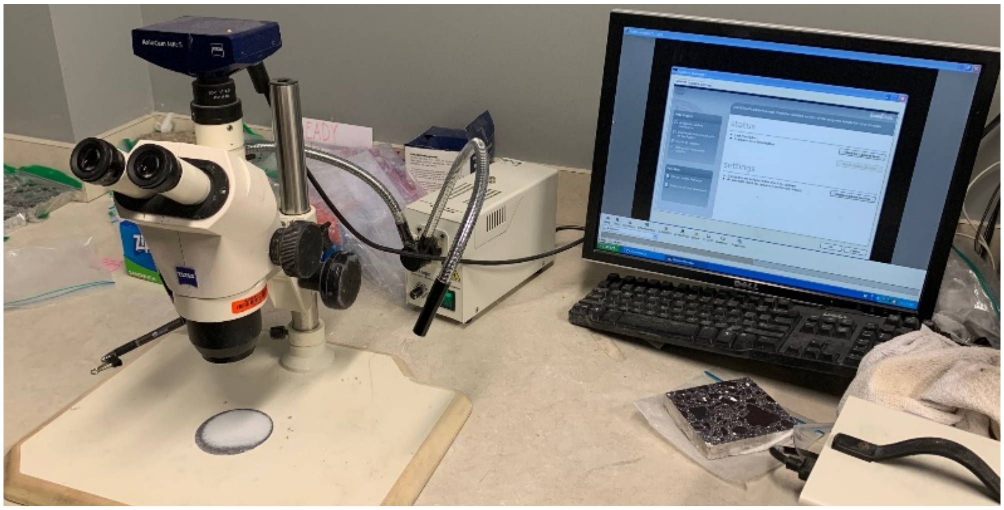
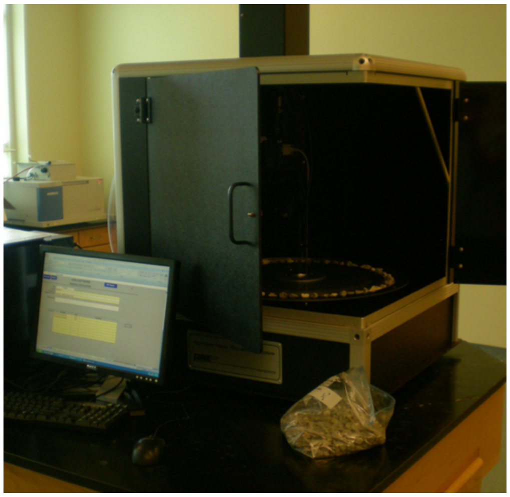
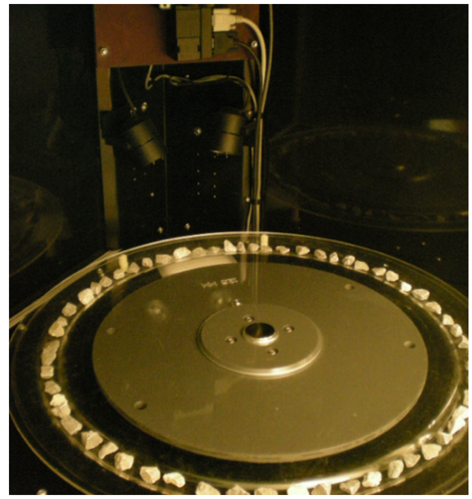


Figure 2- 3 shows the microscope device with a mounted camera to capture particle images.

2.3.2.2 AIMS II

The **A**ggregate **I**maging **S**ystem (AIMS II) was developed to analyze aggregate characteristics such as angularity, shape, and texture of an aggregate particle [38, 39]. As shown in Fig. 2-4, the AIMS II uses variable microscope-camera systems and lighting modes to capture images that are used for shape analysis. Studies have shown that AIMS II test provides repeatable and sensitive results [38, 39]. For fine aggregate, only the angularity and the form 2D of particles are measured by the AIMS II system because they are smaller in size in comparison to coarse aggregate.





(a) **(b)**

Figure 2- 4 displays (a) outside components and (b) loading plate of the AIMS II instrument.

2.3.2.3.1 Sample preparation for AIMS II

From each fine aggregate source, a sample was sieved into individual sieve sizes from No. 4 (4.75 mm) to No. 200 (75 µm), then, washed, and dried. 150 particles were collected from each of the sieve sizes except the No.4 sieve size only requires 50 particles. Each set of particles was placed on the sample tray for testing as shown in Fig. 2-4 (b). Then, the AIMS II system captured digital images of the aggregate particles, analyzed the images, and provided statistical and graphical data of the shape properties of the specimens [38, 39].

2.3.2.3.2 Angularity and Form 2D measurements with the AIMS II

The angularity is measured by comparing the particle radius in a certain direction to an equivalent ellipse with the same aspect ratio. This is shown in Fig 2-5(a). It quantifies changes along the boundaries of a particle using an index scale that ranges between 0 to 10000. The sharper the particle boundaries, the greater the gradient angularity index.

The Form 2D is a measurement applied on fine aggregate particles where 2-D images are used to quantify the form of a particle, as shown in Fig. 2-5 (b). It is expressed in a form index that ranges between 0 to 20 and it is calculated using the following equation [38, 39]:

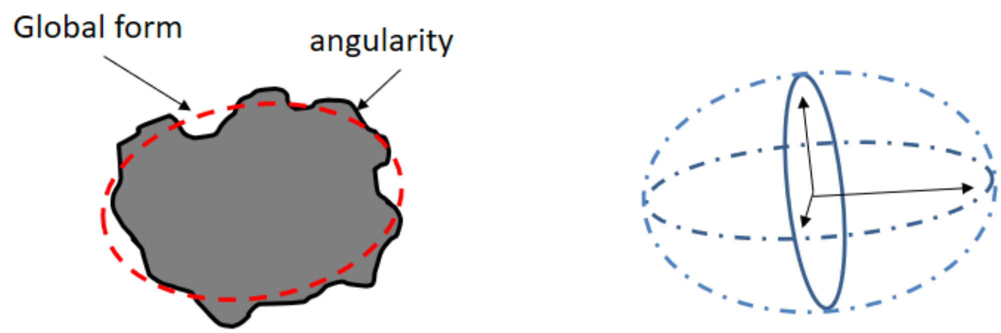
$$\boldsymbol{Form2D} = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{R_{\theta+\Delta\theta} - R_{\theta}}{R_{\theta}} \qquad \textbf{(eq. 4)}$$

Where,

R_θ : radius of the particle at an angle of θ

$\Delta\theta$: incremental difference in the angle θ

The results from the angularity and form is shown with a cumulative distribution as this makes it easier to compare the results.



(a) Angularity **(b) Form**

Figure 2- 5 provides a visual illustration of (a) the angularity and (b) the form [38].

2.3.2.4 Uncompacted Void Content

The Uncompacted Void Content as per ASTM C1252 [40] is a simple and straight forward test to quantify the angularity of fine aggregate. The aggregate should be washed and dried before using one of the three gradations. This work used a standard gradation outlined in Method A and it is shown in Table 2-3.

Table 2- 3. Standard Gradation of ASTM C1257-Method A

Individual sieve size	Mass (g)
No. 8 (2.36 mm) to No.16 (1.18 mm)	44
No. 16 (1.18 mm) to No.30 (600 μm)	57
No.30 (600 μm) to No.50 (300 μm)	72
No.50 (300 μm) to No.100 (150 μm)	17
Total	**190**

The set of fixed mass was chosen so that the gradation of the manufactured sand did not impact the measurement of the angularity. The aggregate gradation of the manufactured sand will be investigated in other testing. The angularity of the particles is measured by measuring the mass of the sample poured into a calibrated cylinder by flowing through a standard funnel as shown in Fig. 2-6. The sample was tested twice and an average value was taken. The standard deviation was always ≤ 0.33% as specified in the test method.

As the particles become more angular then they tend to interlock with one another, this prevents uniform packing and leads to higher voids between the particles. As the particles become more rounded and smoother then the particles tend to pack easier and this leads to a lower content of voids or a higher mass. This is known as the uncompacted voids content and it is calculated as follows:

$$\boldsymbol{U} = \frac{\boldsymbol{V} - \frac{\boldsymbol{F}}{\boldsymbol{G}} \times \mathbf{100}}{\boldsymbol{V}} \qquad \textbf{(eq. 5)}$$

Where,

U: uncompacted voids content (%)

V: volume of the cylindrical (ml)

F: sample mass (grams)

G: dry bulk specific gravity of the fine aggregate

Figure 2- 6 shows the setup for uncompacted void content apparatus

2.3.2.5 Uncompacted Void Content of the combined fine aggregates

Manufactured sand and natural sand have different uncompacted voids contents. Therefore, when they are blended together, the combined uncompacted voids content of the blended fine aggregates will be dependent on the content of each sand. To be able to calculate the combined uncompacted voids content of a blend of natural sand and manufactured sand, the rule of mixtures equation was used. The rule of mixtures equation is a weighted mean utilized to calculate various properties of a composite materials such as mass density [41, 42]. In this work, the rule of mixture equation was used to calculate the angularity and texture of blended fine aggregates, expressed in a combined uncompacted voids content. Further, several blends of manufactured sand and natural sand are tested to validate the equation as shown in Table 2-4

$$\text{Voids content of the combined fine aggregates} = \frac{100}{\frac{\text{P1}}{\text{voids content 1}} + \frac{\text{P2}}{\text{Voids content 2}}} \quad \textbf{(eq. 6)}$$

Where,

P1: weight percentage of the natural sand

P2: weight percentage of the manufactured sand

Voids content 1: uncompacted voids content of the natural sand

Voids content 2: uncompacted voids content of the manufactured sand

Table 2- 4. Comparison between a Calculated Uncompacted Voids Content and an Actual Uncompacted Voids Content of a Blended Fine Aggregates

Blended sands (individual uncompacted voids content)	Combined Uncompacted Voids Content	
	Calculated	Tested (S.D.)
MS7 +NS1 (49.0% - 38.6%)	43.1%	43.2% (0.10%)
MS1 + NS1 (41.0% - 38.6%)	39.7%	39.8% (0.08%)
MS5 + NS1 (45.5% - 38.6%)	43.0%	43.1% (0.07%)
MS5 + NS1 (45.5% - 38.6%)	42.0%	42.2% (0.12%)

It can be seen from Table 2-4 that there is no significant difference between the results obtained by conducting the uncompacted voids content test on combined fine aggregates and the calculated ones.

2.3.3 Mixture design

The combined aggregate gradations investigated were plotted within the Tarantula Curve. To investigate the impact of the manufactured sand on the concrete performance, two sets of concrete mixtures were evaluated. In one set of concrete mixtures, the as-received gradations of the manufactured sand sources were used when they were blended in concrete mixtures. In the other set of concrete mixtures, sieved manufactured sand sources were used when they were blended with the natural sand in concrete mixtures. While the first set of mixtures measured the impact of the differences in the manufactured sand gradations and combined uncompacted voids contents, the second set of mixtures used a fixed set of gradations and allowed the shape of the combined sand to change to measure the impact of the angularity properties of manufactured sands.

2.3.3.3 Concrete mixture with manufactured sands with as-received gradations

In the field, concrete producers would use the manufactured sand with the as-received gradations. Therefore, the focus of this section was to evaluate the impact of using the manufactured sand on the concrete workability performance due to differences in the different sources. A control mixture, made with natural sand, was used as shown in Table 2-5. Then, five manufactured sand sources used in this study replaced the natural sand by volume in an incremental manner in which as the volume of the manufactured sand increased, the combined gradation of the fine aggregate portion changed as shown in Fig. 2-7, due to the coarseness of the manufactured sand gradation. This incremental replacement of natural sand with manufactured sand is done so that variable fine sand volumes (above, at, and below the previously published fine sand limit for the Tarantula Curve) could be achieved. This was done to investigate the variability in the impacts of using the manufactured sand on concrete workability performance from one source to another.

Table 2- 5. Mixture Design for the control mixture

Material	Mass (lbs/yd^3)	Mass (kg/m^3)
Coarse Aggregate	1347	799
Intermediate Aggregate	647	348
Natural Sand	1157*	686*
Manufactured Sand	varied	varied
Cement	489	290
Fly ash	122	73
Water	275	163
WR	6 oz./cwt	3.5 ml/kg

* These are the values with no manufactured sand added.

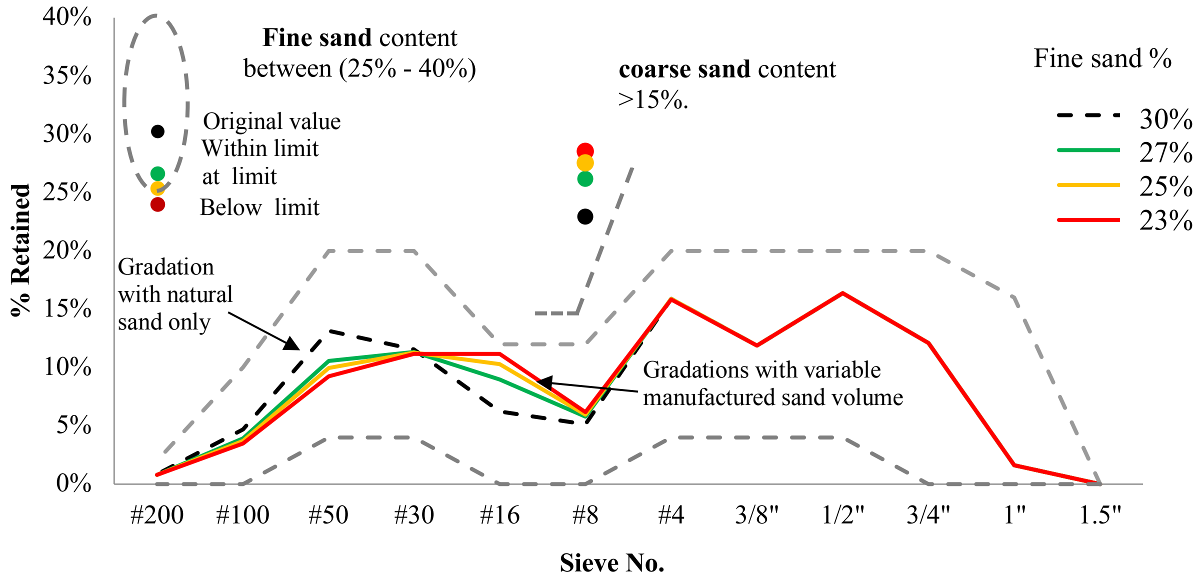


Figure 2- 7 shows Changes in the combined fine aggregate gradations due to the increase in manufactured sand volume.

2.3.3.4 Concrete mixtures with manufactured sands of a fixed gradation

The aim of this section was to study the impact of the manufactured sand shape properties, measured by the uncompacted voids content, on the concrete workability. The variability in the gradations between the tested manufactured sand sources was eliminated by sieving each sand source to a single gradation. This allowed the difference in performance of the sands to be investigated. The control mixture design shown in Table 2-5 was used. Three different aggregate gradations were investigated and the original gradation of the control mixture was plotted to show the changes in the gradation and the fine sand content due to the increase in the manufactured sand volume. The investigated gradations have fine sand contents above, at, and below the previously published fine sand limit for the Tarantula Curve. This is shown in Fig. 2-8. This was done to study the shape of the manufactured sand particles on the concrete workability performance.

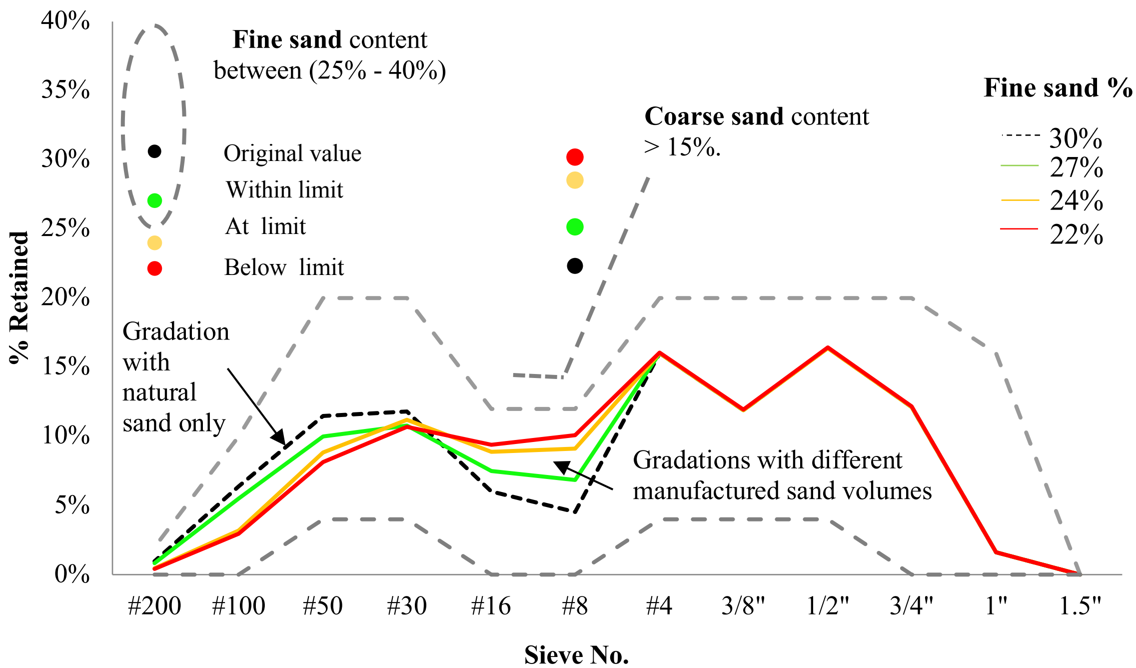


Figure 2- 8 plots the combined aggregate gradation shown on the Tarantula Curve for different fixed sand gradations.

2.3.4 Mixing procedure

The aggregates were collected from the stockpiles and brought into a temperature-controlled laboratory room at 73 °F for a minimum period of 24 hours before mixing. Then, the aggregates were placed in a mixing drum and spun in order to take representative samples for a moisture correction. At the time of mixing, all coarse and fine aggregates were loaded in the mixer along with 2/3 of the water content and mixed for three minutes to make the mixed materials to be homogeneous and approach the saturated surface dry condition (SSD). Subsequently, the cementitious materials were added along with the remaining water and mixed for three minutes. The produced mixture rested for two minutes and the sides of mixer were scraped. After the rest period, the admixtures were added and the concrete was mixed for another three more minutes. The resulted concrete mixture was tested using the workability performance scale, which will be described below.

2.3.5 Concrete testing

This study aimed to investigate the workability behavior of concrete mixtures containing manufactured sand. The workability of the concrete is defined as how easy it is to mix, place, consolidate, and finish the concrete [1]. Concrete workability can be measured by a variety of methods, such as the Slump Test (ASTM C143) [43] or the Box Test AASHTO TP 137 [44]. However, no current workability test can accurately measure and communicate whether the workability parameters such as the consistency, the flowability, and the finishability can be satisfied [31, 32]. Therefore, in this research a workability performance scale was used to determine the workability of the concrete mixtures. The details on how this scale was developed can be found in Cook [32]. This workability performance scale is a combination of four tests: The Slump Test, the Float Test, the ICAR Rheometer Test, and the Visual Observation Test, which are used to assess the flowable concrete workability parameters such as consistency, finishability, and flowability. These four workability tests were combined and used to assess an overall workability performance ranking as discussed in Cook [32].

2.3.5.3 Slump Test

The Slump Test (ASTM C143) has been a well-known test for measuring the consistency of fresh concrete. This test has been historically used to communicate the general workability of fresh concrete. However, the slump does not directly measure how well the concrete can be mixed, placed, consolidated, or surface finished. Furthermore, it has been difficult for any developed workability test to indicate all the workability parameters for the specific application [32]. Nevertheless, the slump test has continued to be used within the industry due to the test being simple, fast, and economical.

2.3.5.4 Float Test

The Float test was developed to measure the finishing process [32]. It consists of a sample form with dimensions of 70 cm by 91 cm (2 ft by 3 ft) and a depth of 9 cm (3.5 in.), a modified bull-float, a template with three standard holes, 25 mm (1 in.) in diameter and height, and a strike-off board as shown in Fig. A1 in the appendix. The sample form is filled with concrete and three standard holes were created. Then, the modified bull-float was placed on one end and moved forward and backward as described in Fig 2-9. The number of passes to close the holes were counted. Also, the number of passes to achieve a smooth surface was counted. The Float Test procedure is summarized in the appendix and more details can be found in Cook [32]. Fig. 2-9 shows a brief description of the Float Test method.

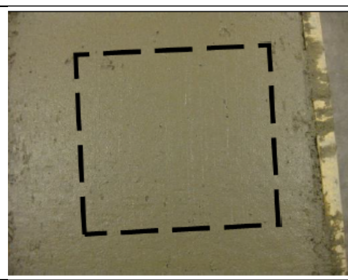
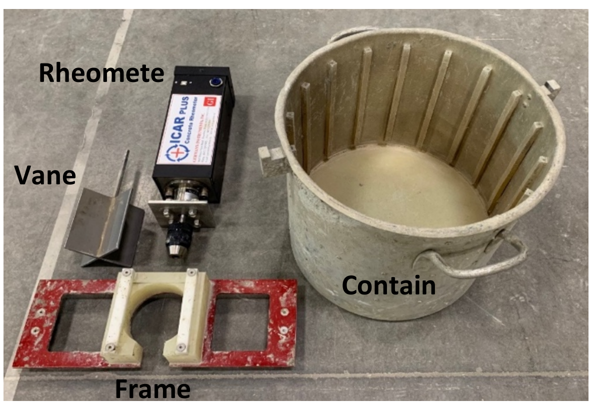
	
Step 1	Step 2
After placing and leveling the concrete with a strike-off board, place template on the form and insert the 1" diameter dowel into the concrete to create a hole	Place bull float on the surface. With a fixed upward tilt of 2 degrees, move the bull float at a constant forward motion of 0.5ft/sec until it reaches the form. (This is one pass.)
	
Step 3	Step 4
Using only the middle 1.5 ft^2 area, determine the texture scale and closing of the holes with Fig. A2 and Fig. A3 in the appendix	If the texture was a 3 or greater or the hole was not removed, the bull float passed back and forth until the texture was 2 or smaller and the hole closed.

Figure 2- 9 provides the Float Test procedure steps. (acquired from Cook [32])

2.3.5.5 ICAR Rheometer Test

Three important parameters can be measured by using the ICAR Rheometer [45]. First, the static yield stress, which is the minimum stress required to initiate a movement in the fresh concrete. The plastic viscosity is another parameter that represents the resistance to flow when the static yield stress is exceeded. Lastly, the dynamic yield stress can be measured. This is the minimum amount of stress that is required to maintain movement in concrete [45].

The ICAR Rheometer consists of a container with strips on the sides to prevent slippage, a vane with fixed dimensions, five inches in height and diameter, a programmed motor to run the torque at specified speeds, and a laptop with the ICAR Rheometer program to run the test. The minimum space between the vane and the wall of the container must be at least four times the maximum aggregate size. Fig. 2-10 shows the ICAR Rheometer components.



(a)

(b)

Figure 2- 10 displays (a) ICAR Rheometer components and (b) assembled ICAR.

The Rheometer Test [45] was conducted by hand scooping the freshly mixed concrete into the container. Then, the Rheometer was reset in the air and then inserted vertically into the container of concrete. Using the laptop, the static growth test was conducted first to measure the static yield stress. Subsequently, the flow curve test was conducted to measure the dynamic yield stress and plastic viscosity.

2.3.5.6 Visual observation

Another approach to investigate the workability of the concrete is through visual observation. This approach provides helpful insights and guidance to evaluate the workability. To visually assess a concrete mixture, five categories were developed by Cook in order to make the visual observation approach more consistent [32]. These categories are listed with a brief explanation: Cohesion, which is assessing the ability of a concrete mixture to stay together. Richness, which is assessing the sand and paste proportioning amounts in a mixture. Finishability, which is measuring the effort required to adequately finish a concrete surface. Flowability, which is assessing the effort required to continuously move the concrete. Stiffness, which is measuring the effort required to initiate movement in concrete [32]. A brief procedure to perform the visual observation is provided in the appendix and the full details and concepts behind the visual observation technique can be found in Cook [32].

2.3.5.7 Overall Workability performance

The overall performance scale to evaluate the workability of a concrete mixture was developed by Cook. It combines the assessments collected from four different tests into an overall workability performance ranking. Table 2-6 shows the workability performance scale and the criteria for each test.

Table 2- 6. Performance Scale for Concrete Workability (modified from Cook)

Workability Performance Scale	**Slump** (mm)	**Visual observation**	**ICAR Rheometer**			**Float test**	
			Static yield stress (pa)	Dynamic yield stress (pa)	Plastic viscosity (pa/sec)	Hole removal (passes)	Texture removal (passes)
Excellent (1)	203 to 152	1	<1000	<250	<10	1 to 2	1 to 2
Good (2)	152 to 102	1 to 2	1000-1500	250-500	10 to 15	3 to 4	3 to 4
Moderate (3)	102 to 51	2 to 3	1500-2000	500-1000	15 to 20	5 to 6	5 to 6
Poor (4)	51 to 0	3 to 4	>2000	>1000	>25	7 to 8	7 to 8
Unusable (5)	0	4 to 5	Too stiff	Too Stiff	Too Stiff	+9	+9

The overall workability performance for a concrete mixture is determined by comparing each of the four workability test results to the workability performance scale shown in Table 2-6. Since each performance scale in Table 2-6 has a numerical range, an overall average number can be calculated for a concrete mixture, which can be converted back into a scale as the following: excellent (0-1), good (1-2), moderate (2-3), poor (3-4), and unusable (4-5). An example of obtaining an overall workability performance for a concrete mixture is provided in Table 2-7.

Table 2- 7. Example Conversion of the Workability Tests into an Overall Performance Rank

Workability Test	**Results example**	**Performance scale**	Avg. numerical value for performance	Overall workability performance
Slump	127 mm	Good (2)		
Visual observation	1	Excellent (1)		
Static Yield Stress	1503 Pa	Moderate (3)		
Dynamic Yield Stress	459 Pa	Good (2)		
Plastic Viscosity	19 Pa	Moderate (3)	**2.4**	**Moderate**
Float Test (holes)	6	Moderate (3)		
Float Test (Texture)	5	Moderate (3)		

2.3.5.8 Curing and concrete compressive strength

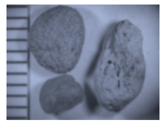
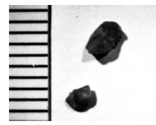
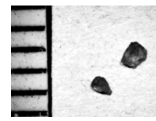
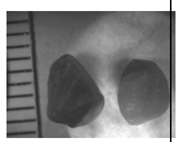
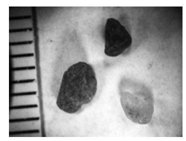
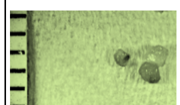
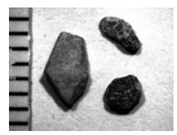
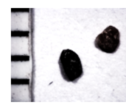
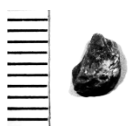
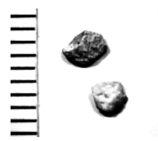
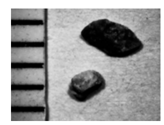
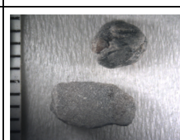
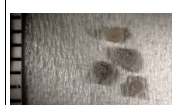
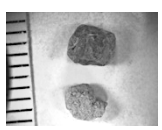
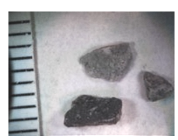
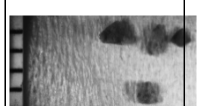
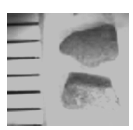
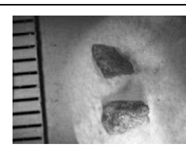
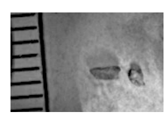
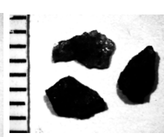
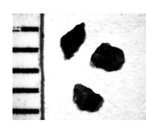
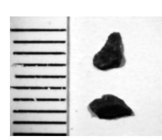
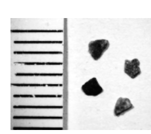
Standard cylinder molds were used for the compressive strength test with a size of 100x200 mm (4 × 8 in.). Molds were filled and consolidated as per ASTM C31 [46]. The samples were stored in a temperature-controlled and moisture-controlled room for curing purposes, as specified in the ASTM C31. Concrete compressive strength test was conducted at 7-day and 28-day on hardened concrete in accordance with ASTM C39 [47].

2.4 Results and discussion

2.4.2 Particle distribution and angularity of manufactured sand

The difference between the natural and manufactured sands can be visually distinguished as the natural sand had more rounded particles, while manufactured sand had more angular particles. Micro images were captured for representative particles taken from each sand source to illustrate the particle angularity visually. Table 2-8 shows the photos, the uncompacted voids content (ASTM C1257 Method A) of each sand source, and key visual observations. These visual observations also match the changes in the numerical values from the uncompacted voids content. The uncompacted voids were observed to increase as the angularity increased. More details are in the Appendix.

Table 2- 8. Angularity Measurements of Each Fine Aggregate Source

Sand Source	ASTM C1257 Method A	No. 8	No.16	No. 30		Observed Angularity
NS1 Silica, Quartz	38.6%				Well Rounded	Well rounded
NS2 Silica Quartz	38.3%					Rounded
MS1 Limestone-clast conglomerates	41.0%					Sub-rounded
MS2 Limestone-Biosparite	43.9%					Sub-angular
MS3 Limestone-Biosparite	44.1%					Angular
MS4 Limestone-Biosparite	45.1%					Angular
MS5 Limestone-fossiliferous & Igneous	45.4%					Angular
MS6 Gabbro-igneous	48.0%				Very Angular	Very Angular
MS7 Dolomitic siltstone & Reagan and glauconitic sandstone	49.0%					Very Angular

The AIMS II test was used to directly measure the angularity and the form of each sand source. Table 2-9 provides the mean AIMS angularity index and the form 2D index for each sand source with each standard deviation (SD), while Fig. 2-11 and Fig. 2-12 show the angularity and the form 2D of the particles for each sand source in a cumulative percent of particles. The charts are divided into four angularity zones: low, moderate, high, and extreme. One way to compare the different particles is to highlight the mean AIMS angularity index or the values for 50% of the particles and determine the zone. With this comparison, it can be seen that the natural sand has the lowest mean AIMS angularity index followed by different manufactured sands.

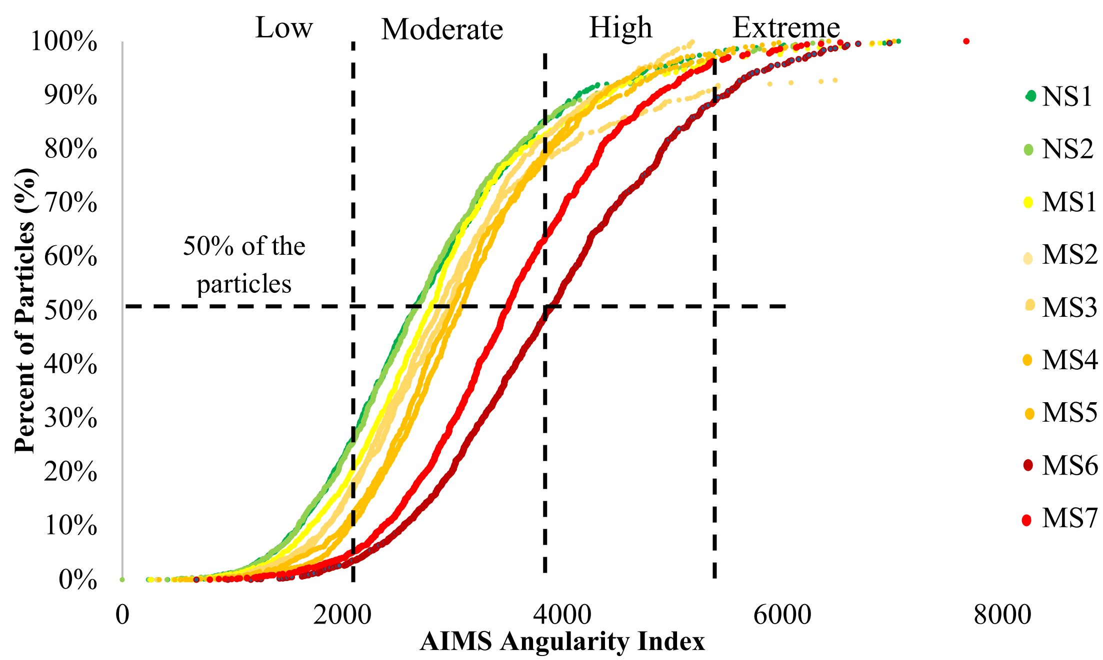


Figure 2- 11 shows AIMS II angularity distribution for the fine aggregate particles.

This same approach has been used to quantify the aggregates with the AIMS form index. The mean line is shown in Fig. 2-12. The natural sand has the lowest form index when compared to the manufactured sands. As the form index of manufactured sand sources increased, the AIMS form index curves were pushed toward the high zone meaning that the particles were getting more elongated and flakier. For example, MS6 and MS7 have more than 50% of their particles in the high form zone.

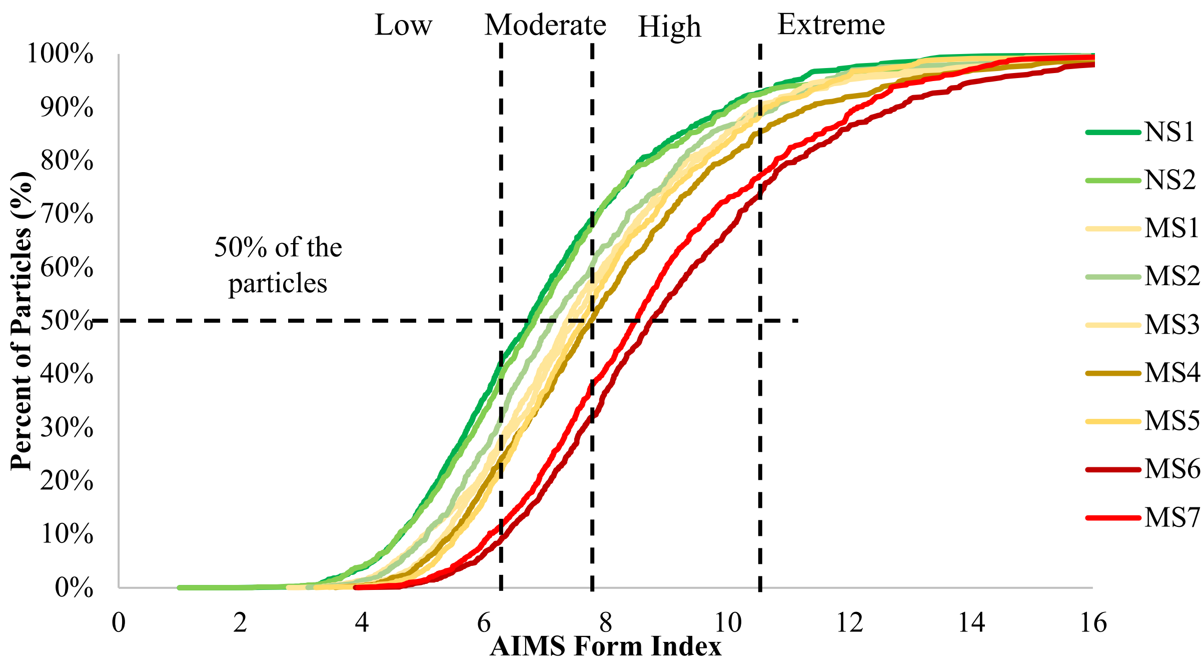


Figure 2- 12 shows the AIMS II Form distribution for the fine aggregate particles.

The uncompacted void content test was conducted to indirectly measure the angularity and texture of each sand source. This was based on using a standard gradation and measuring the ability of the particles to loosely pack together. The void contents of the natural sand and manufactured sand based on this standard gradation are reported in Table 2-9.

Note that the combined uncompacted voids content of fine aggregates used in each concrete mixture was calculated and reported in Table A4 in the Appendix.

Table 2- 9. Angularity, Form 2D, and Uncompacted Voids Content Comparisons of Different Sand Sources

Sand Source	NS1	NS2	MS1	Blnd1	Blnd2	MS2	MS3	MS4	MS5	MS6	MS7
AIMS Angularity index	2420	2406	2551	--	--	2594	2810	2804	2872	3612	3280
SD	99	26	14	--	--	66	80	84	95	58	77
AIMS Form index	6.41	6.43	7.09	--	--	6.82	7.24	7.51	7.44	8.59	8.35
SD	0.17	0.13	0.14	--	--	0.15	0.11	0.08	0.15	0.20	0.10
Uncompacted void content (%)	38.6	38.4	41.1	42.0	43.0	43.9	44.1	45.1	45.4	48.0	49.0
SD (%)	0.09	0.07	0.19	0.07	0.12	0.30	0.19	0.17	0.12	0.04	0.04

Note: blank cells of "--" indicate that the AIMS II was not conducted on the sand source. "Blnd" indicates that manufactured sand was blended with natural sand to obtain a specific uncompacted voids content.

2.4.2.3 Comparing Uncompacted Void Content Test to AIMS II Angularity and Form data

A similar trend can be observed for the data obtained using the uncompacted void content, Method A, and the AIMS II in sorting the angularity from the lowest to the highest. The relationship between the uncompacted void content, Method A, and the two AIMS parameters is shown in Fig. 2-13 and Fig. 2-14. The R2 value for both correlations was found to be 0.80 or higher. This shows a good correlation between the uncompacted voids content, both of the AIMS parameters, and the visual observations with a light microscope. This means that the rapid, economic, and simple uncompacted voids can provide similar information as the more complicated tests.

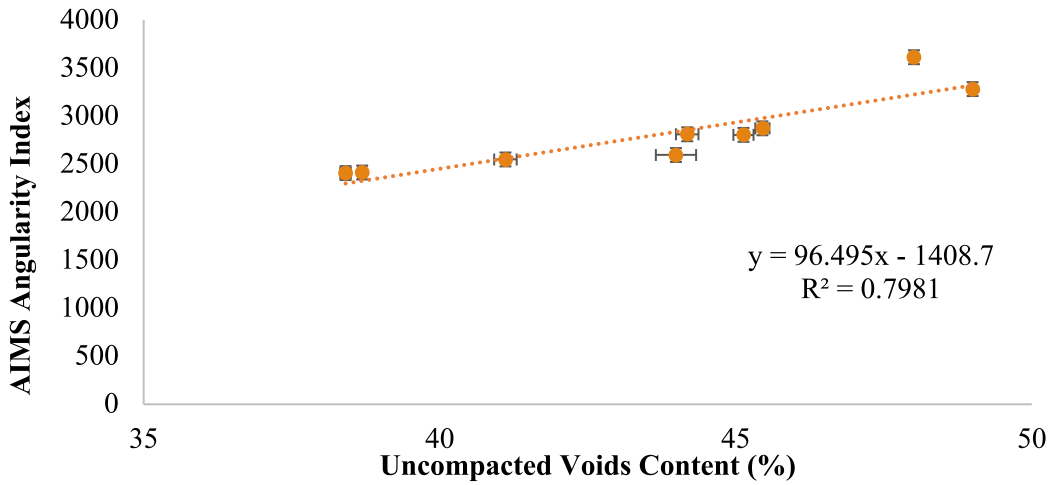


Figure 2- 13 plots the correlation between AIMS II and the uncompacted void content (Angularity).

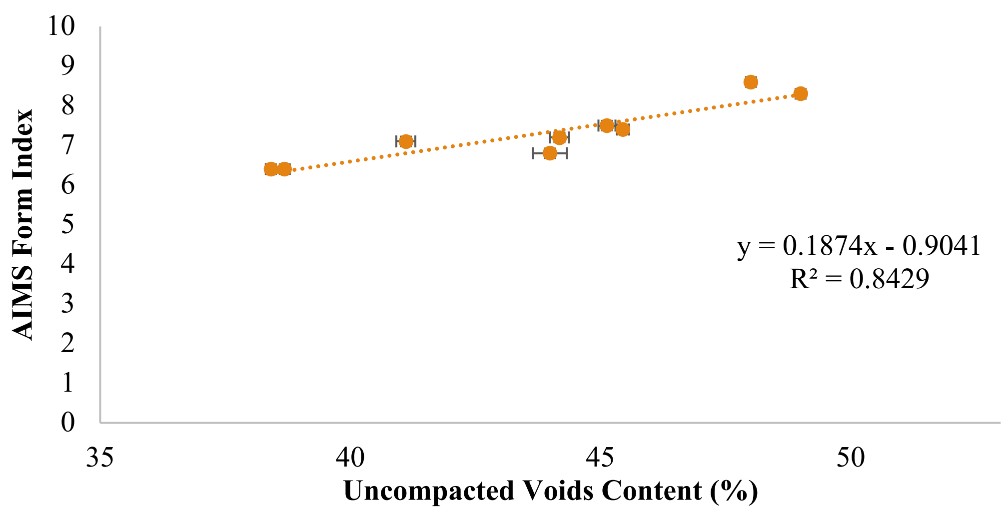


Figure 2- 14 plots the correlation between AIMS II and the uncompacted void content (Form 2D).

2.4.3 Concrete mixture with manufactured sands of as-received gradations

The purpose of this section of this study was to investigate the variable manufactured sand gradations and the uncompacted voids contents and their effects on the workability of the concrete. This was done by using the as-received gradations of five manufactured sand sources when they incrementally replaced the original natural sand by the volume of fine aggregate so that the fine sand contents (sum of the No. 30 (600µm) to No. 200 (75 µm)) are varied (above, at, and below the limit). Detailed results can be found in the Appendix. Fig. 2-15 plots the mixtures for different levels of workability compared to the fine sand content, replacement of manufactured sand, and the combined uncompacted voids content. The color of each data point changes based on the workability performance. Also, the range of manufactured sand replacement by volume is shown numerically for each series of data points for fixed fine sand volume. For these mixtures, the volume of the manufactured sand increased as the fine sand content decreased. This occurs because the manufactured sand has a coarser gradation in comparison to natural sand. One should notice that as the fine sand content decreased or as the manufactured sand content increased, the workability performance decreased. This reinforces how the fine sand content in a combined aggregate gradation plays an essential role in the workability of concrete.

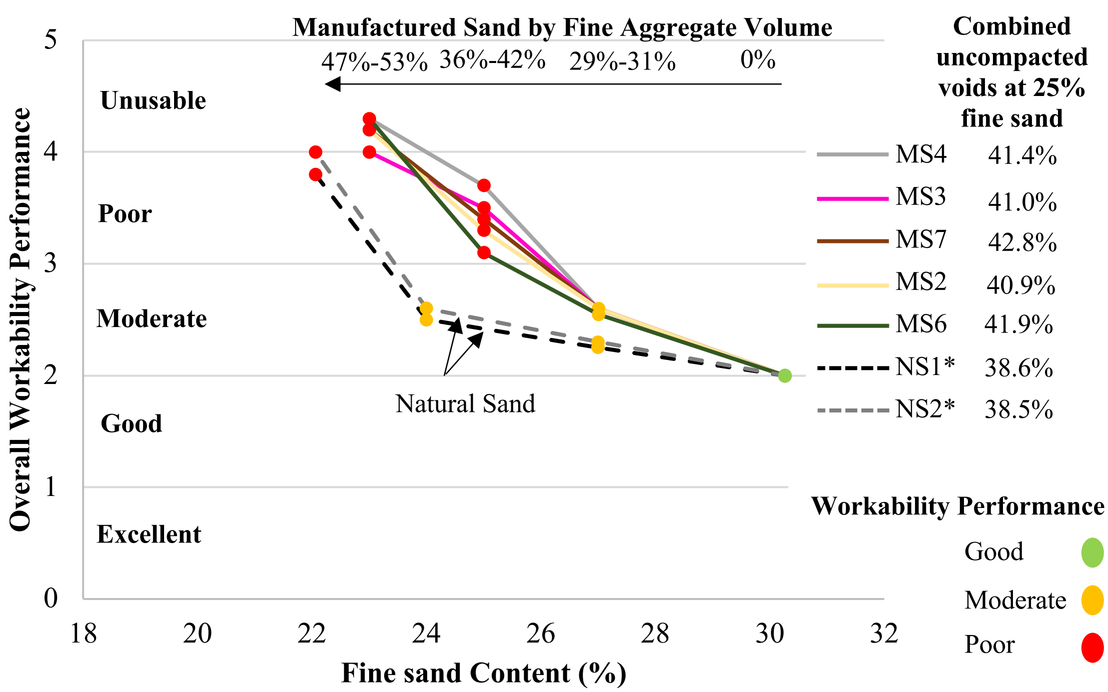


Figure 2- 15 shows overall workability performance versus different fine sand volumes and combined uncompacted voids contents. Note: NS1* and NS2* are natural sands with a fixed gradation.

An important observation from Fig. 2-15 is how the volume of manufactured sand replacement impacted the performance of the mixture in comparison to mixtures with natural sands. This work shows that the manufactured sand can be used between 29% and 31% replacement of the natural sand and still achieve mixtures that are easy to finish and have acceptable workability. However, when the replacement levels are higher, then the workability performance becomes unusable.

When the fine sand content reached 25% in the mixture, the performances for all of the manufactured sands were poor, and the performance varied. At this fine sand content, the amount of manufactured sand replacement varied from 36% to 42%. The uncompacted voids content is also included in Fig. 2-15, and it is also variable. It is important to note that even though the replacement levels and uncompacted voids content were variable, the workability of the mixture was consistently poor. So, no conclusions can be drawn beside the importance of the fine sand content. The relationship between the uncompacted voids content and the workability will be investigated in the next section.

It is important to emphasize that the replacement level of the manufactured sand is not always an acceptable method to estimate the performance. However, the boundaries of the Tarantula Curve should be used with the combined gradation with a particular focus on the fine sand content in the combined gradation.

2.4.4 Concrete mixture with manufactured sands of a fixed gradation

This section aims to investigate the effect of the uncompacted voids content of manufactured sand on the concrete workability. This was done by sieving sands with different uncompacted voids contents and blending them to meet a fixed gradation. Detailed results can be found within the appendix. Fig. 2-16 plots the mixtures with a fixed sand gradation for the different levels of workability compared to the fine sand content, replacement of manufactured sand, and the combined uncompacted voids content. Note that each line represents mixtures made with a different sieved sand source. The color of the dots on each line represents a workability performance. More details are reported in the appendix.

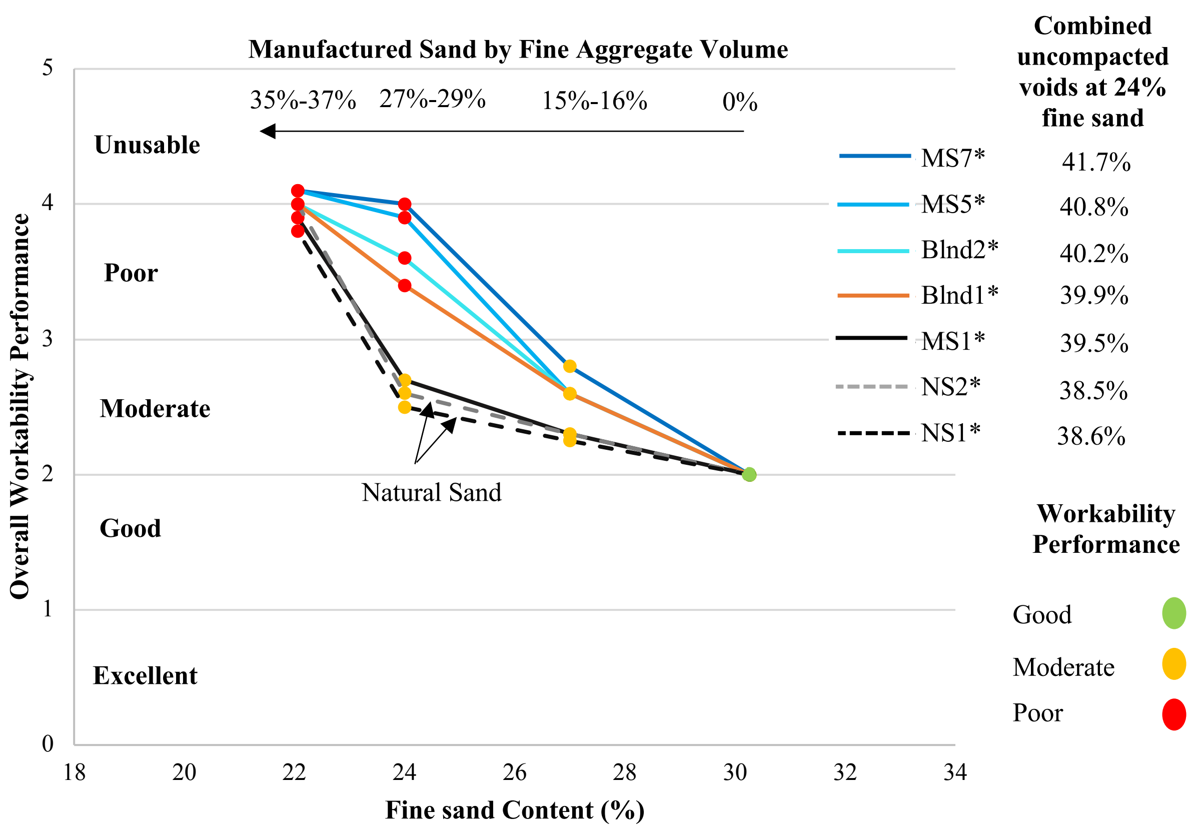


Figure 2- 16 plots overall workability performance versus different fine sand volumes and combined uncompacted voids contents. Note that (*) means that the sand source has a single gradation.

Fig. 2-16 shows that as the fine sand content decreased, the workability also decreased. This reduction in fine sand also coincides with an increase in the manufactured sand replacement level. One can observe that the mixtures with a 30% manufactured sand replacement in Fig. 2-15 had moderate workability while the mixtures with 30% of manufactured sand replacement in Fig. 2-16 had poor performance. This difference in performance is caused by differences in gradation. This shows the importance of fine sand gradation in the workability of a concrete mixture.

Fig. 2-16 also allows the impact of the shape of the sand to be investigated because all the mixtures have the same aggregate gradation. The mixtures with the highest uncompacted voids content consistently showed a lower workability performance than mixtures with lower uncompacted voids content.

The impact of the particle shape is easiest to observe when the fine sand content is 24% as there is such a significant difference in performance. The two mixtures that used natural sands and the manufactured sand with the lowest uncompacted voids content (MS1 with 39.5%) showed very similar performance, and all the other manufactured sands had poor workability.

One important observation is that the difference in the uncompacted voids content is only 0.4% and 0.7% between MS1 and Blnd1 and Blnd2, respectively. However, there was a significant difference in the workability performance despite having the same gradations. This seems to indicate that the uncompacted voids content may not thoroughly explain the impact on the shape and texture of the manufactured sand on the workability performance of the concrete mixture. It would be helpful to find more manufactured sands with uncompacted voids around 40% and determine how they perform in this testing and more deeply study the shape characteristics of those aggregates.

2.4.5 Determining the minimum fine content to proportion manufactured sand

Since the manufactured sand volume in a concrete mixture is determined by the fine sand content, a minimum fine sand content could be set to be able to proportion manufactured sand in concrete and maintain acceptable workability and finishability. To do that, Fig. 2-17 was created where the fine sand contents were plotted on the X-axis, the combined uncompacted voids contents were plotted on the Y-axis, and the overall workability performances were plotted with different colors.

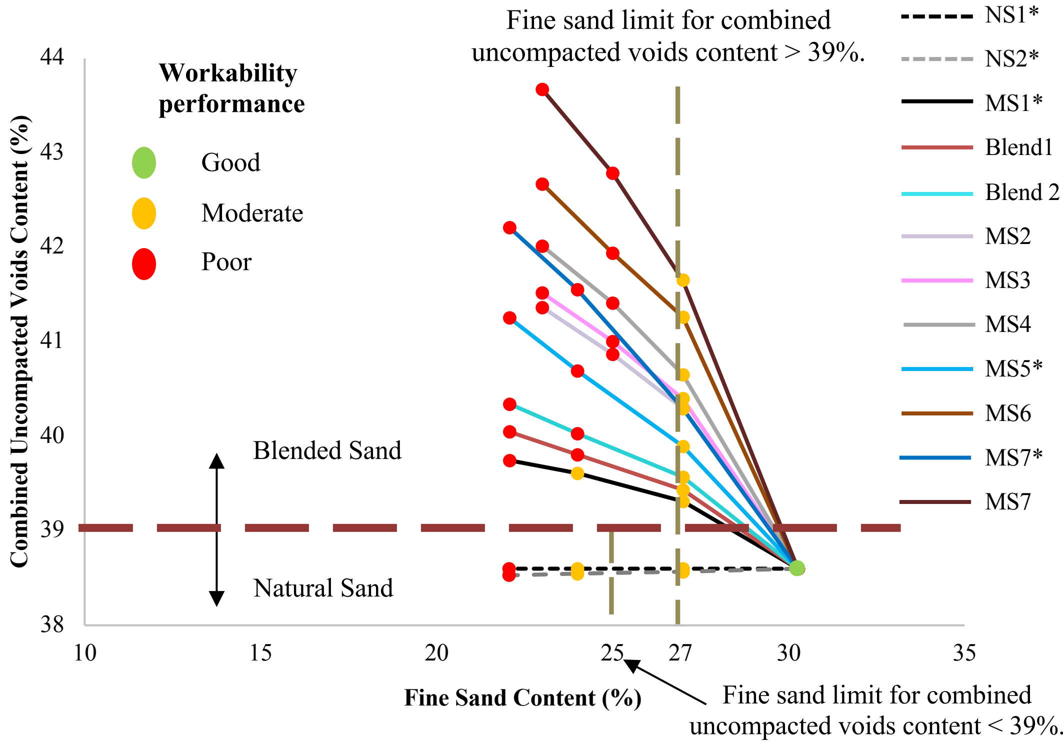


Figure 2- 17 plots the workability performance versus different fine sand volumes and uncompacted voids content.

Note that for mixtures with manufactured sands, the combined uncompacted voids content increased as the amount of manufactured sand increased in the mixture. However, for the mixtures with natural sands, the combined uncompacted voids contents were constant because there is only one sand in this mixture, and it has a fixed uncompacted voids content.

Based on Fig. 2-17, a combined uncompacted voids content limit of 39% was established to differentiate between blended sand and natural sand. For the combined uncompacted voids content of the blended fine aggregates > 39%, the fine sand content of 27% is set as a minimum limit for all the tested manufactured sand sources. These recommendations provide an accurate estimate for all manufactured sand sources but one (MS1). For the combined uncompacted voids content of the blended fine aggregates ≤ 39%, the minimum recommended fine sand content is

25%. This minimum limit matches previous recommendations obtained by Cook [32]. These recommendations apply for the materials and mixtures investigated in this study; however, it would be beneficial to have more sources to expand this work. Fig. 2-18 shows the adjusted Tarantula Curve to proportion manufactured sand in concrete.

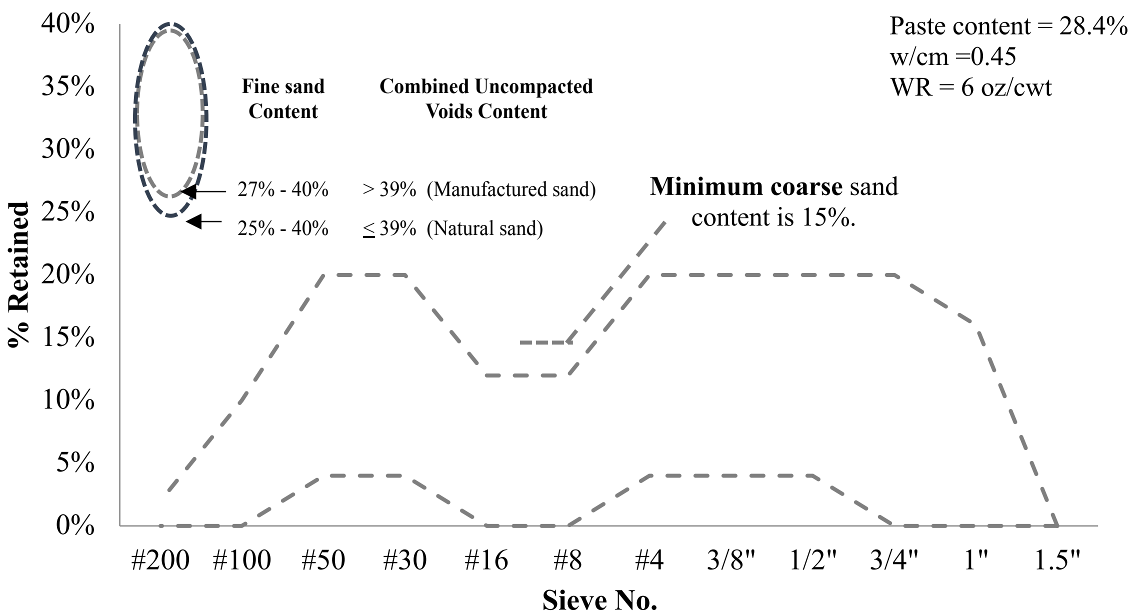


Figure 2- 18 shows the recommended Tarantula Curve to proportion manufactured sand mixtures for flowable concrete.

2.4.6 Compressive strength

The tested mixtures had the same mixtures design as described in section 2.3.3.3 and 2.3.3.4; however, different manufactured sand sources were used to replace the natural sand partially. Fig. 2-19 and Fig. 2-20 plot the compressive strength data at 7-day and 28-day on the Y-axis and the fine sand contents on the X-axis, respectively. Each line contains dots, which represent a fine sand content and compressive strength of a mixture containing a manufactured sand source. The color of the dots on each line represents a workability performance.

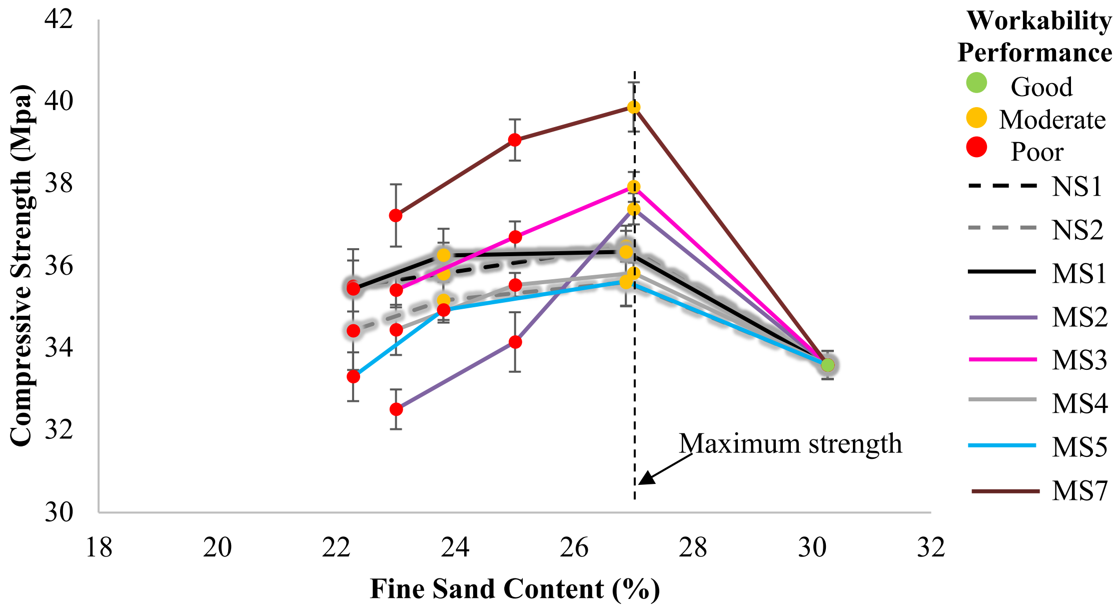


Figure 2- 19 plots the 7-day compressive strength of the concrete mixtures with different manufactured sand sources

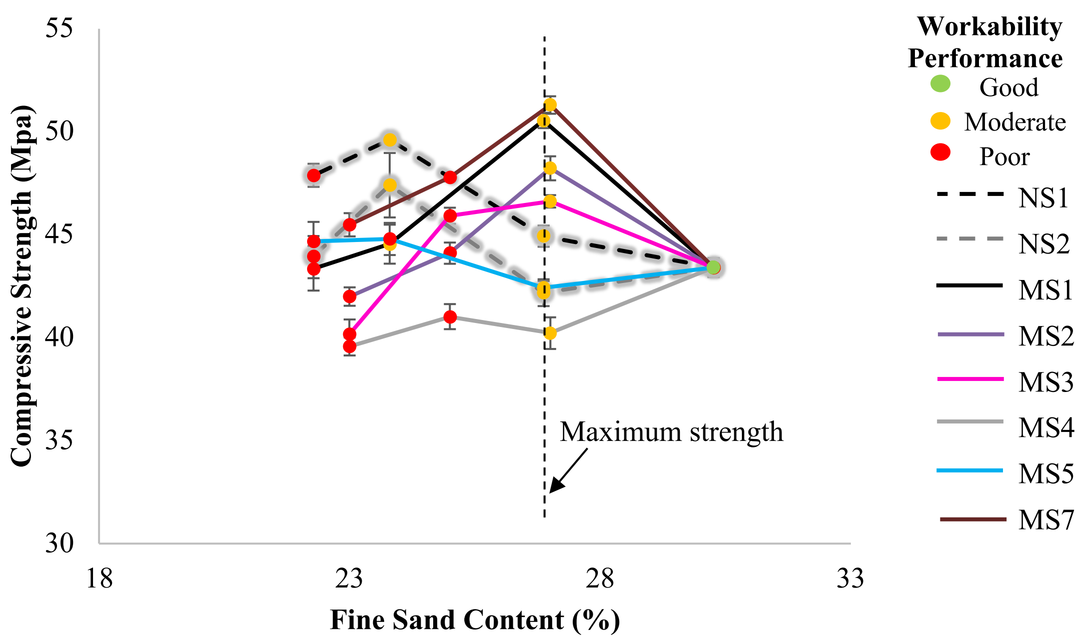


Figure 2- 20 plots the 28-day compressive strength of the concrete mixtures with different manufactured sand sources.

For the 7-day compressive strength, it was observed from Fig. 2-19 that there was a drop in the compressive strength of the concrete mixtures containing manufactured sand right after exceeding the minimum fine sand content limit of 27%. This drop-in strength could be attributed to the change in the workability performance as the mixtures showed a loss in strength when the workability was poor. However, for the mixtures (highlighted lines) containing the sieved natural sands as well as the manufactured sand with the lower combined uncompacted voids contents (MS1), the compressive strength was almost constant and dropped after the fine sand content of 25% was exceeded, or poor workability performance was reached.

For the 28-day compressive strength, there seems to be a drop-in strength if there is poor workability in the mixture but this drop does not appear to be as significant. This difference in behavior could be attributed to the weakness of the paste at 7-days. Thus, the strength of the concrete is dominated by the aggregate. However, in later ages, the concrete strength is a combination of the strength of the paste and the aggregate. This work agreed with other studies findings where the presence of manufactured sand in a concrete mixture can improve the concrete compressive strength [3, 5, 21].

2.5 Practical Significance of this study

The use of manufactured sands has started to be more common in concrete mixtures. However, their usage in concrete can reduce the workability. Due to the little published guidance on a technique for proportioning the manufactured sand in a concrete mixture, this research provides a practical and straightforward approach to design concrete mixtures with manufactured sands. First, this work determined a simple way to quantify the shape of manufactured sands by using the ASTM C 1252-Method A. Next, mixtures were done with these sands with both as received and fixed gradations to determine their performance. It was found that both the shape and the fine sand content were the most important parameters in determining the workability of the mixtures. Based on these findings, new limits for the Tarantula Curve were established. Finally, the work showed how manufactured sands can increase the compressive strength of concrete and how that is tied to the fine sand content in the mixture.

This work shows that successful flatwork can be produced by following the modified guidelines for the Tarantula Curve by replacing 30% of the natural sand with manufactured sand. However, this percentage is not constant for every source, and the acceptable replacement level should be determined by the fine sand content in the mixture. Note that higher replacement levels of manufactured sand may be able to be used if the paste content, water to cement ratio, or admixture dosage is modified. This is an area of future study.

2.6 Conclusion

This work quantified how the shape and gradation of manufactured sand impact the workability of concrete. This was done by comparing several methods to measure the shape and angularity of the manufactured sands. Then, investigating the performance of concrete mixtures by using nine different manufactured sand sources and their impact on the workability and strength. It is essential to know that the manufactured sands used in this study were washed, meaning that the fines amounts were less than the ASTM C 33 limit of 7%. In this work, the fines ranged between 3.17%, 0.70%. Based on this work, several modifications have been suggested to the Tarantula Curve to help guide the use of manufactured sands. The following are the specific findings from this work:

- A linear correlation with R-squared value ≥ 0.80 is made between the Angularity Index, Form 2D Index, and uncompacted voids content percentage measurements from the AIMS II and the uncompacted void content (ASTM C 1252-Method A).
- A combined uncompacted voids content limit of 39% was able to differentiate between manufactured sand and natural sand.

- When blending manufactured sand sources with similar gradation, the workability decreased as the combined uncompacted voids content increased.
- The fine sand content (sum of No. 30 - No. 200) is critical in determining the amount of manufactured sand that can be used in a concrete mixture.
- A minimum fine sand content of 27% is recommended when the uncompacted voids content is >39% or when using blends of manufactured sand and natural sand.
- A minimum fine sand content of 25% is recommended when the uncompacted voids content is $\leq$ 39% or when using natural sands.
- The compressive strength increased as the fine sand content decreased. This trend continued until the workability of the mixture started to decrease. Once the workability decreased, then so did the compressive strength.

This work guides how to produce workable and finishable concrete mixtures that contain manufactured sand. This is an essential step in increasing the use of manufactured sand and producing concrete for satisfactory flatwork.

.

CHAPTER III

EFFECTS OF PASTE CONTENT ON PROPORTIONING CONCRETE MIXTURES WITH MANUFACTURED SANDS

3.0 Introduction

The manufactured sand is a waste product from crushing large stones to produce coarse aggregates. Manufactured sand is widely available and not expensive and so substituting natural sand with manufactured sand, partially or entirely, has started to be more common in the concrete industry [3, 5, 21, 48]. Flatwork applications such as slabs, sidewalks, and parking lots, require concrete mixtures to be flowable, consistent, cohesive, and finishable to be transferred, placed, consolidated, and finished successfully. Previous work showed that manufactured sand shape, gradation, and volume could impact the concrete workability performance [48]. Using manufactured sands in concrete can raise some challenges as they can reduce the workability of concrete. These challenges are attributed to the differences in the shape properties of the manufactured sand particles as opposed to the natural sand. Manufactured sand particles tend to be more angular and textured due to the crushing process [3]. Also, the gradation of manufactured sand rarely complies with the ASTM C33 specification [19]. The manufactured sand could have a high content of fines or particles that pass the No.200 sieve size (75 μm), especially if it is not adequately washed during the manufacturing process. These high fines can increase the surface area and the water demand [3, 20, 21, 32]. There is little guidance to design blended sand concrete mixtures that are flowable and used for flatwork applications.

This work aims to extend the work done by Alturki [48] to provide a practical approach to designing concrete mixtures with blended sand.

3.1 Tarantula Curve

The Tarantula Curve is a practical technique to proportion aggregates for concrete, which has shown success in producing workable concrete mixtures [32]. A significant benefit of the Tarantula Curve is the thorough approach to designing the entire aggregate gradation. Also, it has specific recommendations for different size ranges of sand, as shown in Fig. 3-1.

Previous work, done by Alturki [48], evaluated concrete mixtures with various combined aggregate gradations, specifically the fine aggregate portion, with various manufactured sand sources and replacement levels to the natural sand. These combined gradations were compared to the Tarantula Curve limits. The fine sand contents, the sum of No. 30 (600µm) to No. 200 (75 µm), of these gradations were used to investigate the impact of partially replacing the natural sand with manufactured sand on the workability performance of flowable concrete mixtures for flatwork applications. Also, the uncompacted voids content (ASTM C1252-Method A [40]) was a useful tool to express the angularity and texture of both natural sand and manufactured sand. The manufactured sand has more angular and texture particles than the natural sand. Thus, when blended with natural sand, the combined uncompacted voids content will be a combination of the uncompacted voids contents of the natural sand and the manufactured sand, and its value will increase based on the manufactured sand amount in the blend. It was shown that when the combined uncompacted voids content exceeded 39%, the angularity of the sand impacted the workability of the concrete. When it comes to proportioning the manufactured sand in concrete, the fine sand content was a key factor as it decreased when the manufactured sand replacement level increased and caused the workability performance to decrease.

Thus, modifications were made to the Tarantula Curve to successfully proportion manufactured sand in concrete and still maintain the desired workability performance, as shown in Fig. 3-1 [48].

It is essential to emphasize that the previous work used a fixed paste volume of 28.4% in all the mixtures. The paste consisted of 363 kg/m^3 (611 lbs/yd^3) of cementitious materials, 20% fly ash replacement by mass, w/cm of 0.45, and a water-reducer (WR) dosage of 3.5 ml/kg (6 oz/cwt). At this paste volume, the acceptable manufactured sand replacement level is 30%. Note that higher replacement levels of manufactured sand to natural sand may be used if the paste volume, water to cementitious (w/cm) ratio, or admixture dosage is modified.

One simple and straightforward method to overcome the angularity and gradation challenges imposed by using higher amounts of manufactured sand in concrete is to add more paste to the mixture. This additional paste creates a lubricating layer for the aggregate particles to move in the aggregate matrix [3, 21]. This means that the higher the paste volume of a mixture, the more manufactured sand can be used while maintaining acceptable workability.

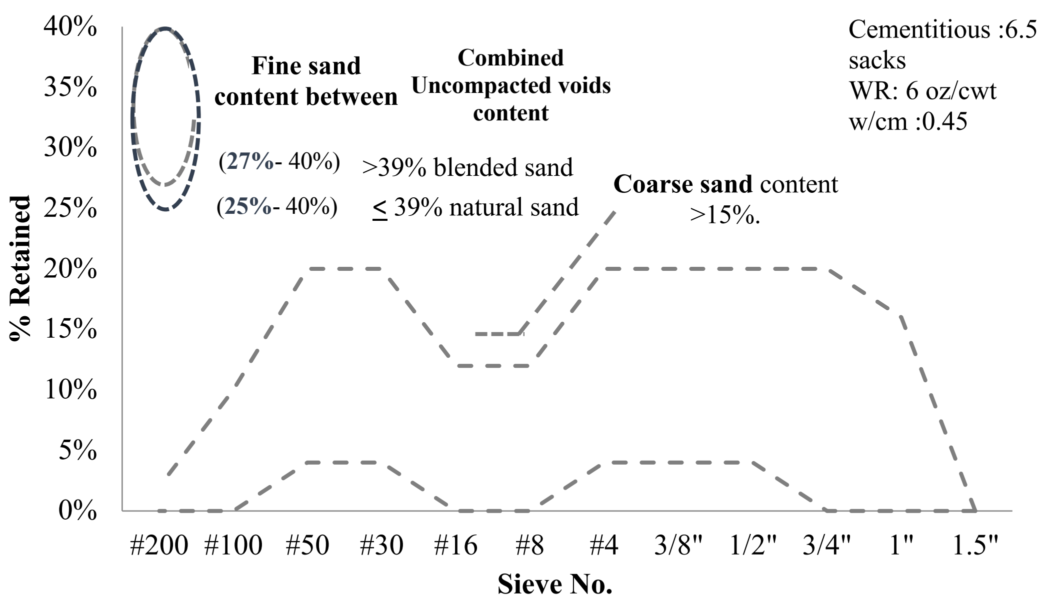


Figure 3- 1 displays the Tarantula Curve limits for both the sieve sizes and the fine and coarse sand volumes.

3.2 Goal of the investigation

This work aims to modify the Tarantula Curve to proportion flowable concrete mixtures for flatwork for blended sands. The combined gradations using the Tarantula Curve will be investigated at different paste volumes based on the workability of the concrete mixtures. Furthermore, the shape and angularity of multiple manufactured sand sources will be incorporated into this investigation to quantify the paste volume, combined gradation, and these aggregate characteristics. This information will also be used to help determine the new boundaries on the Tarantula Curve.

3.3 Experimental methods

3.3.1 Materials

The concrete mixtures were prepared using Type I Portland cement confirming ASTM C150 [33] with a 20% replacement by weight of Class C fly ash meeting ASTM C618 [34]. The oxide analysis for the cementitious materials is reported in Table 3-1. Mid-range water reducer (WR) was a lignosulfonate meeting the Type A/F classification as per ASTM C494 [35].

The coarse and intermediate aggregate used in this study was from a single crushed limestone source. The coarse aggregate was a #57 stone meeting ASTM C33 with a nominal maximum aggregate size of 19 mm (3/4 in.) and the intermediate gradation had a 9.5 mm (3/8 in.) nominal maximum aggregate size. One natural sand and three manufactured sands were investigated in this study from various sources. Note that the manufactured sands used in this study were washed, which means that the fines were less than the ASTM C 33 limit of 7%. In this work, the fines ranged between 3.85% and 0.80%. Table 3-2 shows the fine aggregate properties, and Fig. 3-2 displays the aggregate gradation in individual percent retained according to ASTM C 136 [36].

Table 3- 1. Chemical Composition of the Cementitious Materials

Chemical Components	Portland cement Type I (by mass %)	Fly ash (by mass %)
SiO_2	21.1	16.95
CaO	62.1	40.98
Al_2O_3	4.7	17.22
MgO	2.4	10.28
Fe_2O_3	2.6	7.4
SO_3	3.2	2.41
K_2O	0.3	0.17
Na_2O	0.2	1.13
C_2S	17.8	-
C_3S	56.7	-
C_3A	8.2	-
C_4AF	7.8	-

Table 3- 2. Fine Aggregates Information

Sand Type	Fine Aggregate	Fineness Modulus	Specific Gravity	No. 200 (%)	Fines (%)	Geology	Uncompacted void content (%)
Natural sand (NS)	NS1	2.68	2.61	3.25	0.80	Silica, Quartz	38.6%
Manufactured sand (MS)	MS2	3.06	2.65	1.19	2.10	Limestone-Biosparite	43.9%
	MS3	3.12	2.66	3.17	3.85	Limestone-Biosparite	44.1%
	MS7	3.36	2.76	1.70	1.63	Dolomitic siltstone, Reagan Sandstone and glauconitic sandstone	49.0%

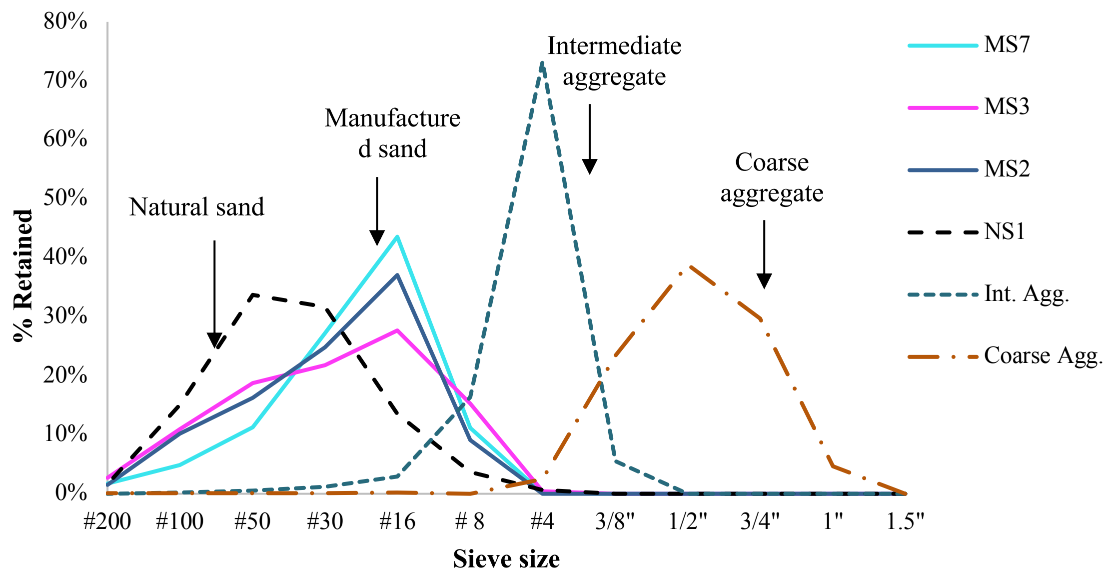


Figure 3- 2 shows the particle distribution of aggregates.

3.3.2 Shape properties of manufactured sand

In this work, the Uncompacted Voids Content Test (ASTM C1252-Method A) was used to quantify the shape of the sand. This method has been shown to correlate well to visual observations and the angularity and shape measured by the AIMS II [48]. The combined uncompacted voids content was used to express the shape properties of the blended fine aggregates (natural and manufactured) by utilizing the following equation [48]:

$$\text{Voids content of the combined fine aggregates} = \frac{100}{\frac{\text{P1}}{\text{voids content 1}} + \frac{\text{P2}}{\text{Voids content 2}}} \quad \textbf{(eq. 7)}$$

Where,

P1: weight percentage of the natural sand used in the fine aggregate portion

P2: weight percentage of the manufactured sand used in the fine aggregate portion

Voids content 1: uncompacted voids content of the natural sand

Voids content 2: uncompacted voids content of the manufactured sand

3.3.3 Concrete mixture design

This study investigated how varying the paste volume would impact the manufactured sand volume in a concrete mixture using the Tarantula Curve. Four sets of concrete mixtures were made. In the first set of concrete mixtures, a control concrete mixture with a known performance was made at a paste volume of 26.2%, 6 sacks of total cementitious materials, 0.45 w/cm, and 3.5 ml/kg (6 oz/cwt) of mid-range WR were used. This mixture design was similar to the one used for concrete mixtures containing natural sand only, as shown in Table 3-3. Next, while keeping the coarse aggregate gradation constant, the natural sand is incrementally replaced by manufactured sand and the change in the workability performance is measured by the workability performance scale, which will be explained in section 3.3.5. As the manufactured sand was added, this decreased the fine sand content in the mixture and increased the No. 16 materials in the mixture. Fig. 3-3 illustrates an example of the effects of incrementally increasing the manufactured sand volume on the combined aggregate gradations of mixtures with a paste volume of 30.6%. This testing is useful as the changes in the workability is measured for different manufactured sand contents.

The paste volume was increased by 2.2% or 1/2 sack of cementitious materials up to 32.8% paste volume with the same w/cm and WR dosage. The natural sand is incrementally replaced by manufactured sand until the mixture showed unusable workability. Table 3-4 shows the paste volumes used for each set of concrete mixtures.

Table 3- 3. Mixture Design with a Paste Volume of 26.2% at 0.45 w/cm & WR of 3.5 ml/kg (6 oz/cwt)

Material	Weight (lbs/cy)	Weight (kg/m^3)
Coarse Aggregate	1380	799
Intermediate Aggregate	680	348
Natural Sand	1189*	686*
Manufactured Sand	Vary	Vary
Cement	452	290
Fly ash	112	73
Water	254	163
WR	6 oz./cwt	3.5 ml/kg

* These are the values with no manufactured sand added.

Table 3- 4. Paste Volume for Each Set of Concrete Mixture

Concrete mixtures	Paste volume %	Cementitious content (sacks)
Set 1	26.2%	6.0
Set 2	28.4%	6.5
Set 3	30.6%	7.0
Set 4	32.8%	7.5
W/cm: 0.45		

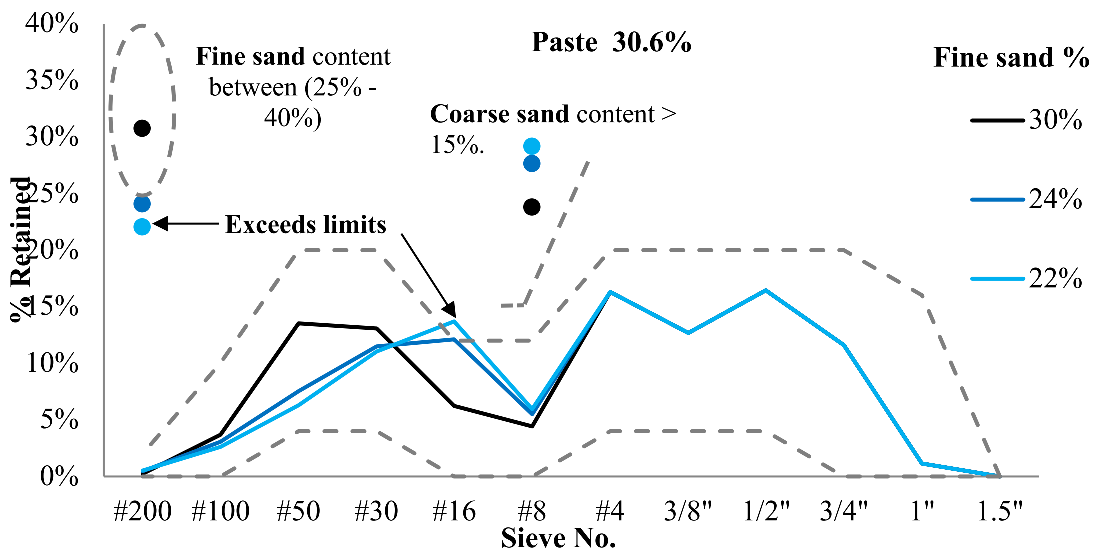


Figure 3- 3 plots an example of combined gradation changes in the control mixture due to the incremental replacement of the manufactured sand (MS7) to the natural sand (NS1).

3.3.3.1 No. 8 and No. 16 sieve limits at different paste volumes

Manufactured sand has a coarser gradation, and as its volume increases in a mixture, the materials retained on the No. 8 or No. 16 sieve will increase and the fine sand will decrease. Finishability issues occur when the gradation exceeds 12% retained on either the No. 8 or the No. 16 sieve [32]. Note that the limits for these sieve sizes are established based on a paste volume ≤ 28.4% and mixtures with natural sand only. This work aims to find the workability limits for the No. 8 and No. 16 sieve for a paste volume of **30.6%** and **32.8%** in mixtures with blended sand.

The gradations investigated are shown in Fig. 3-4 for a paste volume of 30.6%. These gradations show that each mixture exceeds the fine sand limit and sometimes exceeds the limit on the No. 8 and No.16 sieve. The gradations are shown in Fig. 3-5 for the mixtures with a paste volume of 32.8%. Several different gradations above the No. 8 and No. 16 sieve limits were investigated in order to find the threshold for acceptable workability.

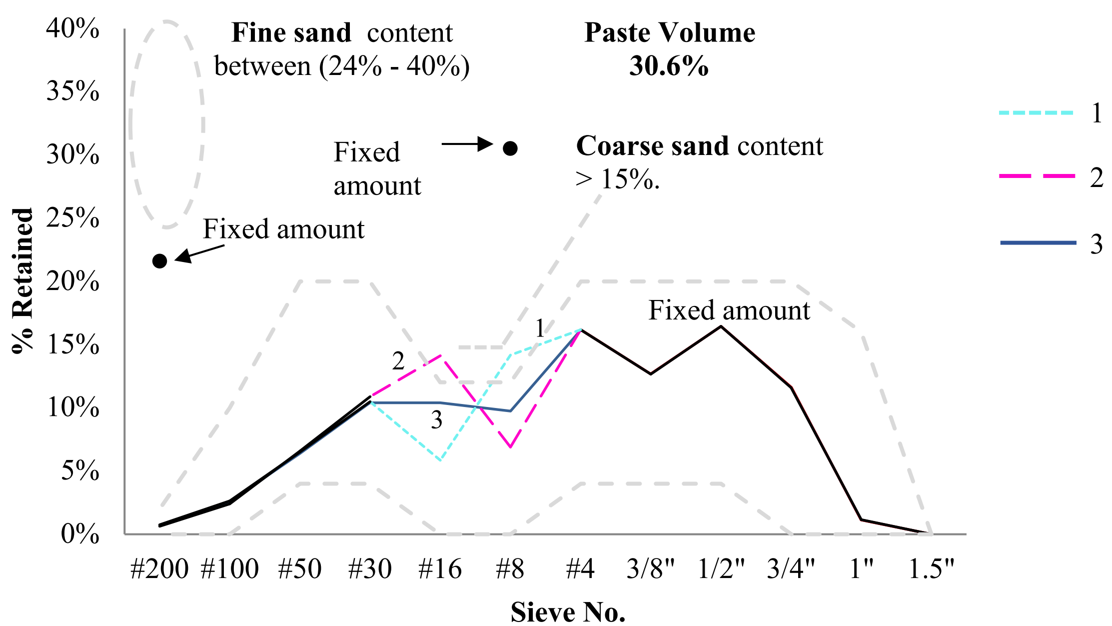


Figure 3- 4 Gradations investigated with a 30.6% paste volume.

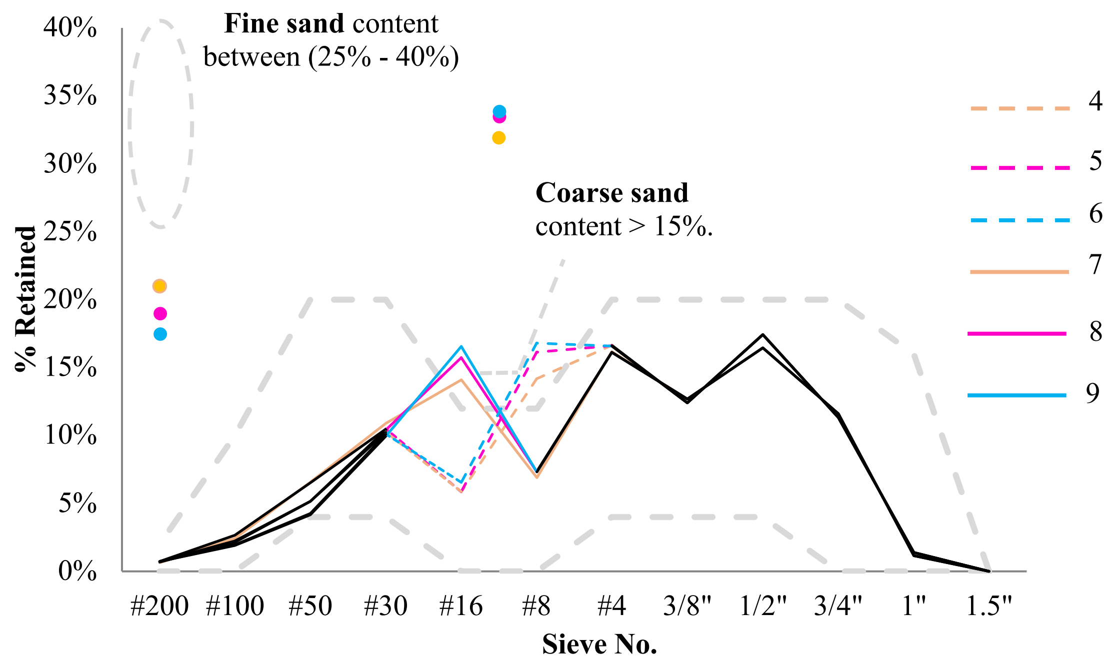


Figure 3- 5 Gradations investigated with a 32.8% paste volume.

The workability performance of these mixtures will be measured, and the appropriate limits for the sieves No .8 and No. 16 will be assigned accordingly.

3.3.4 Mixing procedure

The aggregates were collected from the stockpiles and brought into a temperature-controlled laboratory room at 73°F for a minimum period of 24 hours before mixing. The aggregates were then placed in a mixing drum and spun to take representative samples for a moisture correction. At the time of mixing, all coarse and fine aggregates were loaded in the mixer and 2/3 of the water content and mixed for three minutes to make the mixed materials homogeneous and approach the saturated surface dry condition (SSD). Subsequently, the cementitious materials were added along with the remaining water and mixed for three minutes. The produced mixture rested for two minutes, and the sides of the mixer were scraped. After the rest period, the admixtures were added, and the concrete was mixed for another three more minutes. The resulted concrete mixture was tested using the workability performance scale, which will be described below.

3.3.5 Concrete testing

This study aimed to investigate the workability behavior of concrete mixtures containing manufactured sand at variable paste contents. The workability of the concrete is defined as how easy it is to mix, place, consolidate, and finish the concrete [1]. There are various methods to measure the concrete workability, such as the Slump Test ASTM C143 [43] or the Box Test AASHTO TP 137 [44]. Nevertheless, no current workability test can accurately measure the concrete workability solely. Therefore, in this research, a workability performance scale was used to rank the workability performance of the concrete mixtures. The details on how this scale was developed can be found in Cook [32]. This workability performance scale is a combination of four tests: The Slump Test, the ICAR Rheometer test [45], the Float Test [32], and the visual observation test [32]. More details can be found in Cook [32].

3.3.5.1 Overall workability performance ranking procedure

The overall performance scale combines the assessments collected from four different workability tests into an overall workability performance ranking because each test by itself may not quantify the concrete workability for the desired application. Table 3-5 shows the workability performance scale and the criteria for each test.

Table 3- 5. Performance Scale for Concrete Workability (modified from Cook) [32]

Workability Performance Scale for Each Test	**Slump test** (mm)	**Visual observation**	**ICAR RHEOMETER**			**Float Test**	
			Static yield stress (pa)	Dynamic yield stress (pa)	Plastic viscosity (pa/sec)	Hole Removal (passes)	Texture Removal (passes)
Excellent (1)	203 to 152	1	<1000	<250	<10	1 to 2	1 to 2
Good (2)	152 to 102	1 to 2	1000-1500	250-500	10 to 15	3 to 4	3 to 4
Moderate (3)	102 to 51	2 to 3	1500-2000	500-1000	15 to 20	5 to 6	5 to 6
Poor (4)	51 to 0	3 to 4	>2000	>1000	>25	7 to 8	7 to 8
Unusable (5)	0	4 to 5	Too stiff	Too Stiff	Too Stiff	+9	+9

The four workability test results are compared to the workability performance scale, shown in Table 3-5, to determine the overall workability performance for a concrete mixture. Since each performance scale on Table 3-5 has a numerical scale, a total average number can be calculated for a concrete mixture, which can be converted back into a scale as the following: excellent (0-1), good (1-2), moderate (2-3), poor (3-4), and unusable (4-5).

3.4 Results and discussion

3.4.1 Impact of the paste volume on proportioning the manufactured sand in concrete

This section aims to investigate the gradation limits for different paste volumes of mixtures with blended natural and manufactured sands. This was done by using three manufactured sand sources to replace the original natural sand by the volume of the total fine aggregate in an incremental manner to exceed the fine sand limits.

The workability performance scale from Table 3-5 was used to evaluate the workability of the different mixtures. Detailed workability results can be found within the appendix. Fig. 3-6 shows the workability performance for mixtures with paste volumes of 26.2%, 28.4%, 30.6%, and

32.8% for different fine sand content and the approximate replacement level of manufactured sand. Each manufactured sand is shown in a unique line type, and the paste volumes are shown in different colors. The color of the dots on each line shows the workability performance.

Note that the approximate manufactured sand replacement level is based on the MS7 sand source. The difference in the replacement level between the tested manufactured sand sources was within +/- 10%, due to the gradation variability.

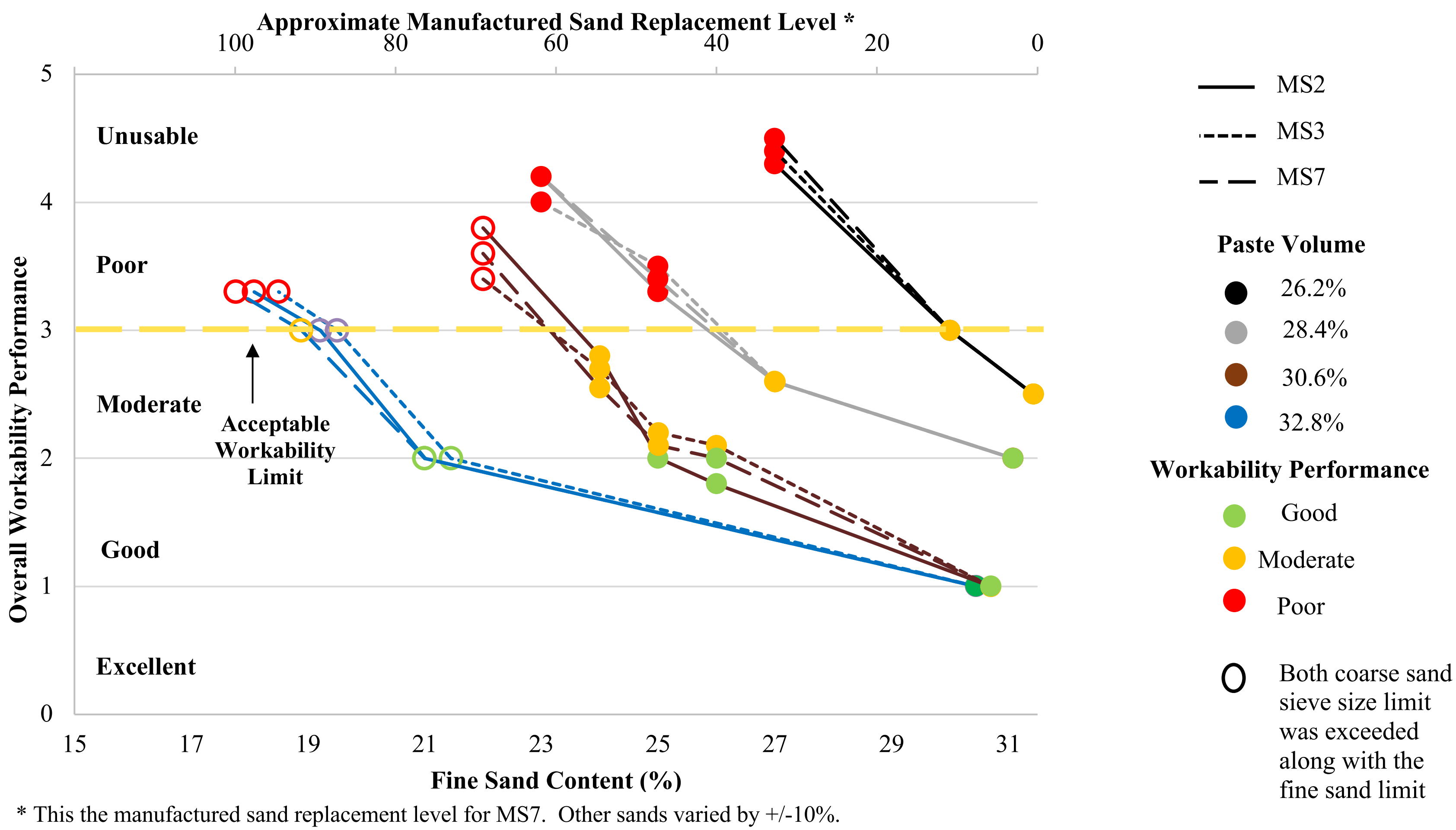


Figure 3- 6 plots the overall workability performance versus different fine sand volumes of mixtures with a paste volume of 26.2%, 28.4%, 30.6%, 32.8%

Figure 3-6 shows that as the manufactured sand replacement level increased, then the fine sand content decreased. As the fine sand content decreased, the workability performance decreased as well. Fig. 3-6 also shows that as the paste volume increased in a mixture, the amount of fine sand content required in the mixture decreased. This shows that the paste is replacing the amount of fine sand needed in the mixture. Further, this also means that the amount of manufactured sand in the mixture can increase.

From Fig. 3-6, one can notice that when the fine sand content is 22% or above, not only the fine sand limit is exceeded, the coarse sand sieve size limit is exceeded, as illustrated by the hollow dots. It can be observed that poor performance was obtained at a paste volume of 30.6% when both the fine sand limit and the coarse sand limit were exceeded. More details about what caused this performance to occur will be provided in the next section. Also, it seems that higher paste volume (32.8%) can overcome both the lack of fine sand and finishability issues due to exceeding the sieve sizes No. 8 or No. 16 original limits. This will be further investigated in the next section.

Table 3-6 shows the combined uncompacted voids for the blended sand sources at different paste contents and fixed fine sand contents that show similar workability performance. These results show no significant difference in these results despite differences in the uncompacted voids content. For example, at a paste volume of 28.4% and fine sand content of 23%, the MS7 mixture with a combined uncompacted voids content of 43.2% has a similar workability performance to the MS3 mixture with a combined uncompacted voids content of 41.2%. Further, different manufactured sands from different geological sources performed similarly. This trend occurred at every fine sand content and each paste volume used in this work, which reinforced the important role of the fine sand content in a combined aggregate gradation of a mixture containing manufactured sand as it impacts the workability performance of concrete. This finding matches previous findings for a broader range of materials [48].

Table 3- 6. The Combined Uncompacted Voids Content for the Blended Sand Sources at Different Paste Volumes and Fixed Fine Sand Contents

Fine sand (%)	18	22	23	27
Paste volume (%)	32.8	30.6	28.4	26.2
	Combined uncompacted voids content			
MS2 (limestone TX**)**	43.9%	42.6%	41.2%	40.4%
MS3 (Dolomite)	44.1%	43.0%	41.3%	40.5%
MS7 (Limestone OK**)**	49.0%	44.9%	43.2%	41.7%
Workability performance	Poor	Poor	Poor	Poor

Table 3-7 summarizes the results from Fig. 3-6 and provides the minimum fine sand content limit, approximate manufactured sand replacement level, and the combined uncompacted voids content at each paste volume.

Table 3- 7. Summary of the Recommended Limits for the Blended Sands.

Paste content (%)	Minimum Fine sand (%)	Approximate Manufactured Sand Replacement level (#) (%)	Combined Uncompacted Voids Range (%)
26.2%	30%	15%	39.6% to 40.3%
28.4%	27%	30%	40.4% to 41.7%
30.6%	24%	55%	41.6% to 43.5%
32.8% (*)	19%	85%	43.5% to 47.5%

(#) These replacement levels are based on one manufactured sand source (MS7), and it varies for other manufactured sand sources.

(*) Note that not only the fine sand limit was adjusted, but the coarse sand sieve sizes limits were also adjusted. More details are shown in the next section.

3.4.2 Limits for No. 8 and No. 16 sieve for blended sands

This section investigates the workability limits for the No. 8 and No. 16 sieve for a paste volume of 30.6% and 32.8% for blended sands. Table 3-8 shows the workability performance of mixtures with a constant coarse aggregate, fine sand content, and coarse sand content, but varying the materials retained on the No 8 and No. 16 sieves. Also, Fig. 3-7 visually shows the gradations of these mixtures with their workability performance.

Table 3- 8. The Workability Evaluation with Fixed Combined Gradations, but Variable Amounts of Materials Retained on the Coarse Sand Sieves at 30.6% Paste Volume.

Gradation	No. 8	No. 16	Fine Sand	Workability Performance
1	Exceeded limit	Within limit	Exceeded limit	Poor
2	Within limit	Exceeded limit	Exceeded limit	Poor
3	Within limit	Within limit	Exceeded limit	Moderate

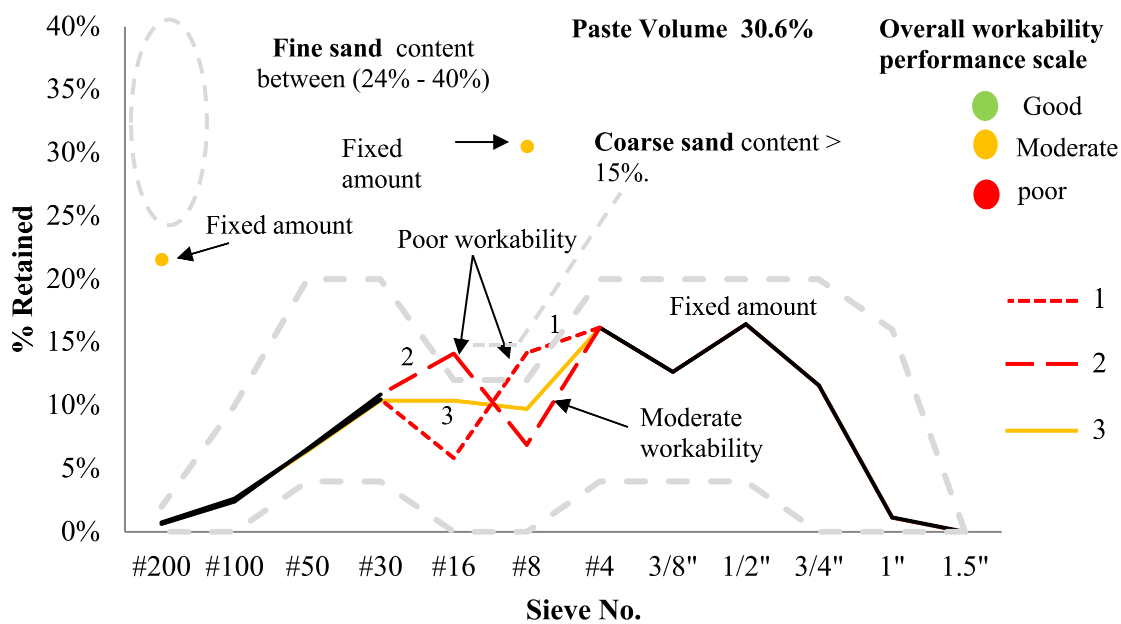


Figure 3- 7 varies the materials retained on the sieve sizes No. 8 and No. 16 with the overall workability performance at a paste volume of 30.6%

Based on Table 3-8 and Fig. 3-7, poor performance occurred due to the finishability issues caused by exceeding the No. 8 or the No. 16 sieve limit of 12%. However, when the limit of those sieves was satisfied with mixture 3, the workability was moderate. This suggests that the original limit of 12% for the No. 8 and No. 16 sieves is valid for mixtures with blended sand and a paste volume of 30.6%. Also, from Table 3-8 and Fig. 3-7, note that even though mixture 3 had fine sand of 22%, the performance was moderate. Thus, the minimum fine sand can be 22% as long as the No. 8 and No. 16 sieve limit of 12% is satisfied.

The workability performance of mixtures with a paste volume of 32.8% with different gradations above No. 8 and No. 16 sieve limits is shown in Table 3-9. Also, Fig. 3-8 visually shows the gradations of these mixtures with their workability performance.

Table 3- 9. The Workability Evaluation with Different Gradations Above the No. 8 and No. 16 Sieve Limits at 32.8% Paste Volume

Gradation	No. 8	No. 16	Fine Sand	Workability Performance
4	14%	<12%	21%	Good
5	16%	<12%	19%	Moderate
6	17%	<12%	17%	Poor
7	<12%	14%	21%	Good
8	<12%	16%	19%	Moderate
9	<12%	17%	17%	Poor

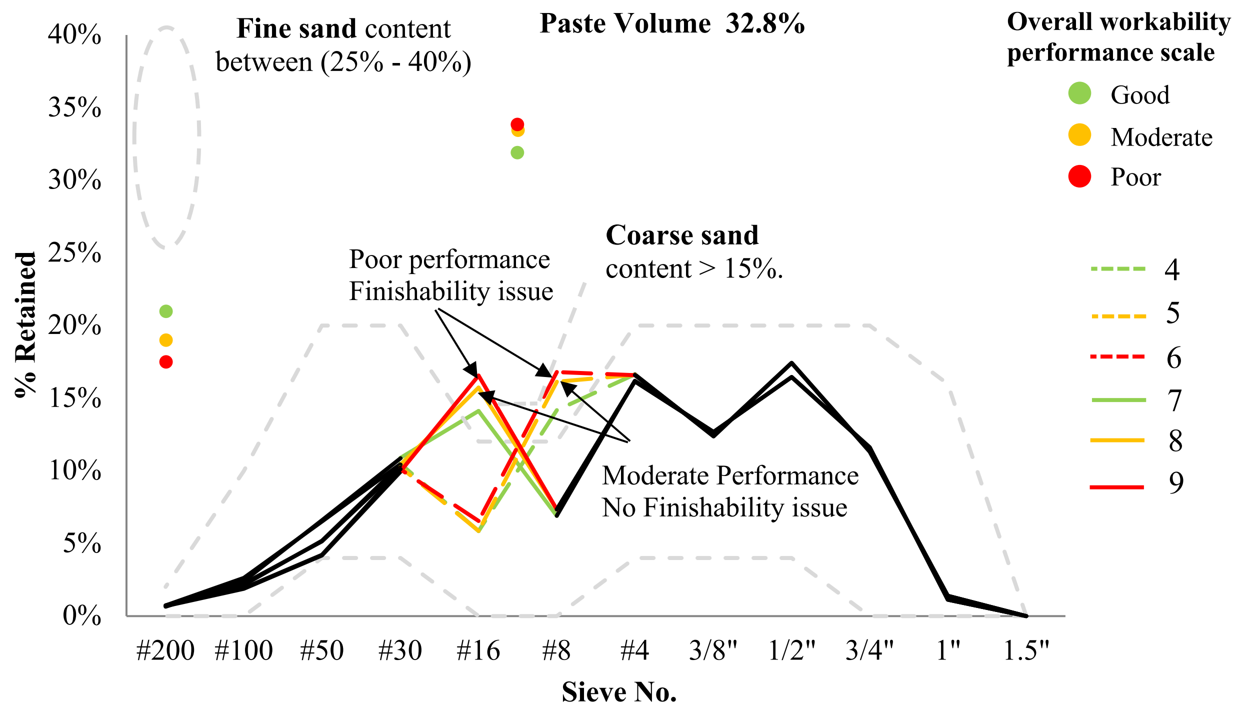


Figure 3- 8 varies the materials retained on the sieve sizes No. 8 and No. 16 with the overall workability performance at a paste volume of 32.8%

Based on Table 3-9 and Fig. 3-8, a paste volume of 32.8% allowed the No. 8 and No. 16 limit of 12% to be extended. The new workability limit for these sieves was found to be 14%. For mixtures 6 and 9, the workability performance suddenly changed from moderate to poor without much change in the materials retained on the No. 8 or No. 16 sieves; however, there are changes in the fine sand content. This shows that there is a synergy between these two parameters that should be investigated in the future. Therefore, it is possible that the poor performance was caused by the lack of fine sand content rather than the further increase of the materials retained on the sieve sizes No. 8 or No. 16. Nevertheless, both the lack of fine sand and the excess of the coarse sand materials retained on the sieve No. 8 or No. 16 likely contributed to the workability performance to be poor.

Based on the data obtained from this study, at a paste volume of 32.8%, the limit for the coarse sand sieve sizes No. 8 and No. 16 was modified to be 14%. This limit was chosen because the results were not sensitive to the fine sand content and so this is a conservative recommendation.

3.4.3 Summary of Tarantula Curve Limits with Blended Sands

Due to the angularity of the manufactured sands blended with the natural sands, the workability limits for the fine sand and the No. 8 and No. 16 sieve limits are modified over mixtures with just natural sand. Fig. 3-9 shows a linear relationship between the paste volume (total cementitious materials sacks) and the fine sand; as the paste volume increased in a mixture with blended sand, the minimum required fine sand decreased. Since the $R^2 > 0.98$, this shows that the linear model does an outstanding job describing the impact of the fine sand on the paste content of the mixture. Fig. 3-10 shows the modified Tarantula Curve to proportion blended sands. The paste volume and fine sand limits are shown along with the modified limit for the No. 8 and No. 16 sieve for a paste volume of 32.8%. This work agreed with other studies that showed that the manufactured sand can be utilized in concrete mixtures with acceptable workability performance [3, 5, 21].

It is important to remember that all the mixtures used in this study had paste properties of 0.45 w/cm, 20% fly ash replacement, and 6 oz/cwt WR. Note that changes to the paste properties can change the workability performance of a mixture containing manufactured sand. For example, using a different w/cm or using a higher dosage of WR in the mixtures could change the workability performance and causes changes in the recommended limits. Keep in mind that any changes in the paste properties could increase or decrease the suggested paste volume. However, the provided recommendations are based on the mixtures and materials investigated in this study.

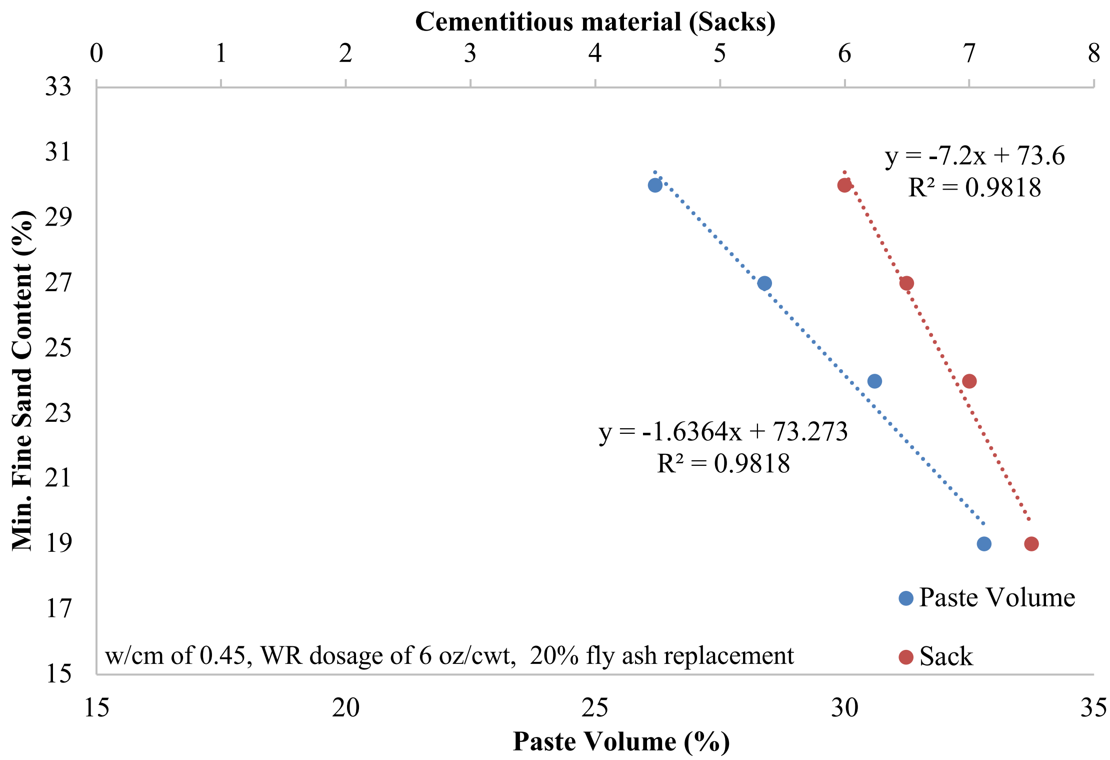


Figure 3- 9 plots the fine sand contents versus each paste volume and cementitious material content for mixtures with blended sand.

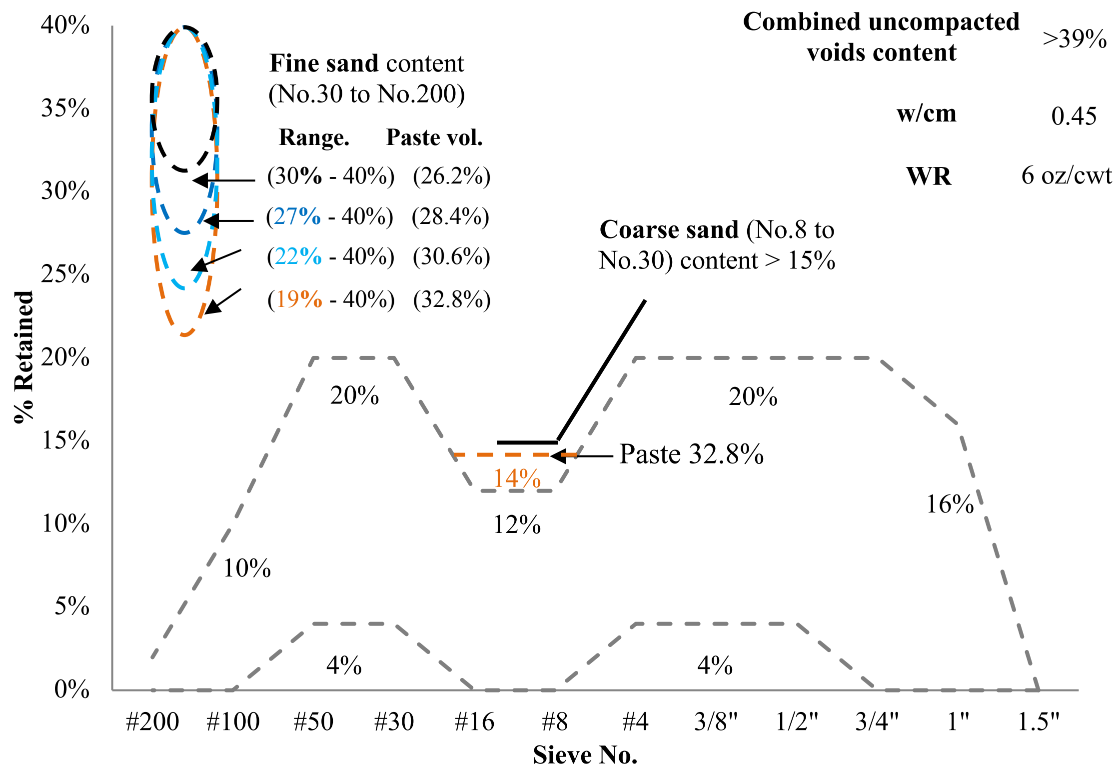


Figure 3- 10 shows the Tarantula Curve with recommendations to proportion manufactured sand in concrete.

3.5 Practical Significance of this study

Due to the availability and low cost of the manufactured sand, there is a strong interest in blending manufactured sand in concrete. However, using manufactured sands in concrete can reduce the workability due to the different shape properties of these sands. This research provided a practical and straightforward approach to design concrete mixtures with manufactured sands. The workability of mixtures with different paste volumes and manufactured sand replacement was evaluated. This work shows that the fine sand content in the Tarantula Curve was an essential parameter in assessing the workability performance of the mixtures. Also, the minimum fine sand content limit in the Tarantula Curve can be modified based on the selected paste volume. Further, it was found that using a paste volume of 32.8% allowed an increased volume of material retained on the No. 8 and No. 16 sieve to be used.

This work shows that successful flatwork concrete can be produced by following the modified guidelines for the Tarantula Curve at each paste volume level. One can proportion the aggregates, including the manufactured sand, to develop a combined aggregate gradation, and plot the combined aggregate gradation on the Tarantula Curve. Then, the paste volume is selected. If the combined aggregate gradation satisfies the specified limits at the selected paste volume, a trial batch can be made and tested to meet the desired workability performance before using the designed concrete mixture in production.

3.6 Conclusion

The manufactured sand was proportioned in concrete using the Tarantula Curve. Note that the manufactured sands used in this study were washed, which means that the fines amounts were less than the ASTM C 33 limit of 7%. In this work, the fines ranged between 3.85%, 0.80%. This work was primarily focused on how the paste volume used in a concrete mixture can allow more manufactured sand to be blended in a mixture. As the manufactured sand content increased in a concrete mixture, the fine sand content decreased, and the coarse sand content increased because the manufactured sand had coarse gradations. The impact of the angularity of the manufactured sand was expressed in the combined uncompacted voids content. The following were key highlights for the results:

- The paste volume in a mixture impacted the minimum required fine sand content to achieve acceptable workability, and so the allowable amount of manufactured sand in the mixture.
- There is a linear relationship between the allowable minimum fine sand content and the paste volume in the mixture. For a paste volume of 26.2% and 32.8%, the minimum fine sand content is 30% and 19%, respectively.
- For a paste volume of 32.8%, the allowable limit on the No. 8 and No. 16 sieve is 14% in order to control finishability problems.

This work guides how to produce workable concrete mixtures with blended sand. It is also an important step to developing a mixture design procedure that combines the aggregate gradation and paste volume in the mixture design. This is an essential step in producing satisfactory flatwork concrete.

CHAPTER IV

THE IMPACTS OF MANUFACTURED SAND ON PUMPING CONCRETE

4.0 Introduction

In some areas, the availability of natural fine aggregates sources (natural sand) is decreasing. This requires natural sand to be brought in from a significant distance, and this will increase the cost of the concrete. Manufactured sand is a by-product of crusher fines that is commonly considered as a waste and so it is not costly. Thus, substituting the natural sand with manufactured sand, partially or entirely, has started to be more common in concrete [3, 5, 16, 21].

Concrete pumps are useful tools to transfer concrete from a ready-mix truck to the desired location on the job site. Pumping concrete is done by pushing the concrete through a pipeline system, made of rigid and/or flexible piping [49]. Also, the pipeline may contain changes in the diameter and direction. Thus, a concrete mixture should satisfy specific properties such as flowability and cohesiveness to provide stability and mobility under pressure. Previous work has shown that the aggregate gradation and characteristics can significantly impact the workability and, subsequently, the pumping pressures [50]. This work aims to extend this work to the performance of manufactured sands.

The manufactured sand has particles that can be angular and textured. Also, it has a gradation that typically does not comply with the ASTM C33 [18, 19]. The manufactured sand could have high content of fines or particles that pass the No.200 sieve size (75 μm), especially if the material is not adequately washed. Consequently, challenges could arise by using the manufactured sands in concrete mixtures as they can reduce the workability performance and make the concrete more susceptible to plugging during the pumping process [16, 17, 20, 21]. Furthermore, there is little published guidance regarding the design of pumpable concrete mixtures with this material. Therefore, this work aims to provide a practical and straightforward approach to designing concrete mixtures with manufactured sand for pumping.

4.1 Tarantula Curve

The Tarantula Curve has been used as a practical proportioning technique for concrete mixtures [32]. Previous work, done by Seader, evaluated concrete mixtures with various combined aggregate gradations and compared them to the Tarantula Curve limits. The pumping pressures of the mixtures were used to investigate the impact of different combined aggregate gradations on the pumpability of the concrete. It was shown that the Tarantula Curve provided useful limits for coarse aggregates, intermediate aggregates, and fine aggregates (natural sand) to produce successful and pumpable concrete mixtures [50]. Also, Seader showed that the fine sand content, the sum of the materials retained on the sieves sizes from No. 30 (600μm) to No. 200 (75 μm), impacted the pumpability performance as follows: an excessive fine sand content led to high stiffness and an increase in pumping pressure, whereas low fine sand content impacted the cohesiveness of concrete and jammed the pump-line, which led to high pumping pressures. Seader suggested that concrete pumping pressure should not exceed 414 kpa (60 psi). This limit corresponds to a 25% increase from the initial pumping pressure for well-performing mixtures, and it is typically translated to a low workability mixture.

One concern with manufactured sands is the shape of the material. Manufactured sands are typically more angular than natural sands. The uncompacted voids content (ASTM C1252-Method A [40]) is a simple and straight forward test to quantify the angularity and texture of fine aggregate particles. From previous work, the shape of manufactured sand particles as measured with AIMS II and with micrograph images was shown to correlate with ASTM C1252-Method A [48]. Further, the combined uncompacted voids content of natural and manufactured sand blends was valuable to proportion flowable concrete mixtures [48].

Another concern with the manufactured sand is the gradation. Manufactured sand has coarser gradation in comparison to the natural sand. The coarseness of the manufactured sand gradation impacts the fine sand content (Sum of No.30 to No.200). Typically, when a manufactured sand volume increases, then the fine sand content decreases. The reduction in the fine sand content will cause the workability performance to become poor when exceeding the specified limit [48].

These findings showed that when the uncompacted voids content of the blended fine aggregate was > 39%, the minimum fine sand content limit was increased from 25% to 27%. However, if the uncompacted voids content was ≤ 39% or when using natural sands, the fine sand content limit was 25%, as shown in Fig. 4-1 [48].

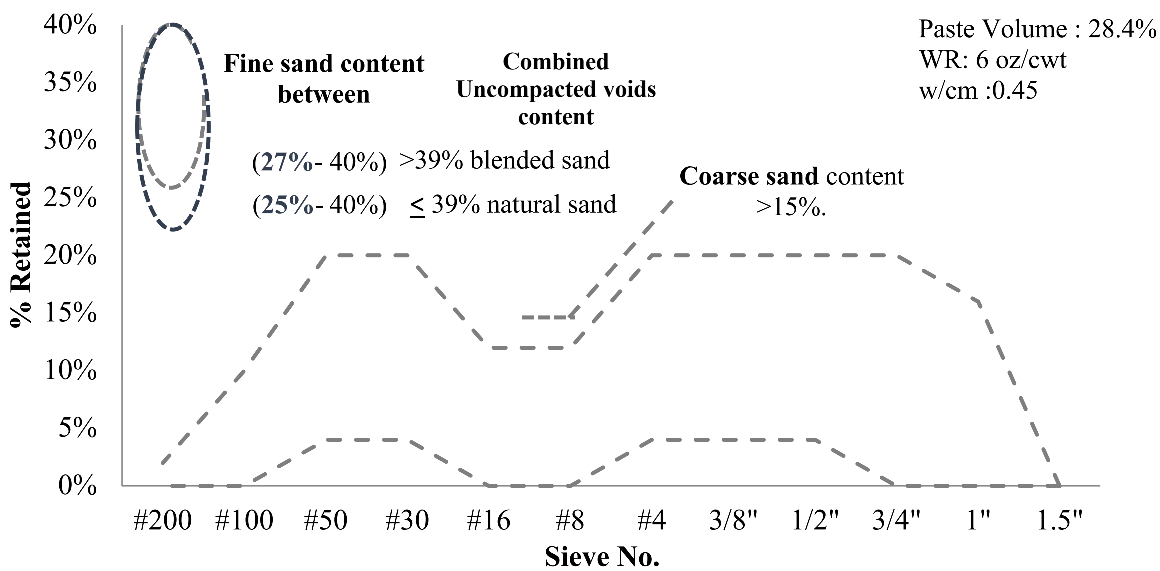


Figure 4- 1 shows the modified Tarantula Curve limits for both the sieve sizes and the fine sand and coarse sand volumes to proportion aggregates.

Note that these modifications were made for flowable concrete. However, in many cases, flowable concrete may require the concrete to be transferred by pumping.

4.2 Goal of investigation

The goal of this study is to investigate the performance of blended natural and manufactured sands in concrete that needs to be pumped. The uncompacted voids contents, along with the fine sand contents, will be compared to the pumping pressures. Next, modified limits will be proposed to the Tarantula Curve to proportion manufactured sands in pumpable concrete. Also, a comparison between the pumpability of mixtures with natural sand only and mixtures with blended fine aggregates will be provided.

4.3 Experimental methods

4.3.1 Materials

The concrete mixtures used Type I Portland cement conforming to ASTM C150 [33] with a 20% replacement by weight of a Class C fly ash meeting ASTM C618 [34]. The oxide analysis for the cementitious materials is reported in Table 4-1. A citric acid [35] was used to at a dosage of 0.25% of the total weight of the cementitious materials. The citric acid was used to delay set approximately 45 hours to allow testing to be conducted without stiffening of the concrete.

Table 4- 1. Chemical Composition of the Cementitious Materials

Chemical Components	Type I (by mass %)	Fly ash (by mass %)
SiO_2	21.1	16.95
CaO	62.1	40.98
Al_2O_3	4.7	17.22
MgO	2.4	10.28
Fe_2O_3	2.6	7.4
SO_3	3.2	2.41
K_2O	0.3	0.17
Na_2O	0.2	1.13
C_2S	17.8	-
C_3S	56.7	-
C_3A	8.2	-
C_4AF	7.8	-

The coarse and intermediate aggregate used in this study was from a single crushed limestone source. The coarse aggregate was a #57 meeting the ASTM C33 with a nominal maximum aggregate size of 19 mm (3/4 in.) and the intermediate gradation had a 9.5 mm (3/8 in.) nominal maximum aggregate size. One natural sand source and three manufactured sand sources were investigated in this study. Note that the manufactured sands used in this study were washed, which means that the fines were less than the ASTM C 33 limit of 7%. In this work, the fines ranged between 2.59% and 0.70%. Table 2 shows the properties of the fine aggregate, and Fig. 4-2 displays the aggregate gradation in individual percent retained according to ASTM C 136 [36].

Table 4- 2. Fine Aggregates Information

Sand type	Fine aggregate	Fineness modulus	Specific gravity	No. 200 %	Fines %	Geology	Uncompacted voids content %
Natural sand (NS)	NS1	2.68	2.61	3.25	0.80	Silica, Quartz	38.6
Manufactured sand (MS)	MS1	4.13	2.67	0.20	0.70	Limestone- clast conglomerates	41.0
	MS4	4.26	2.63	1.27	2.59	Limestone-Biosparite	45.1
	MS7	3.36	2.76	1.70	1.63	Dolomitic siltstone, Reagan Sandstone, and glauconitic sandstone	49.0

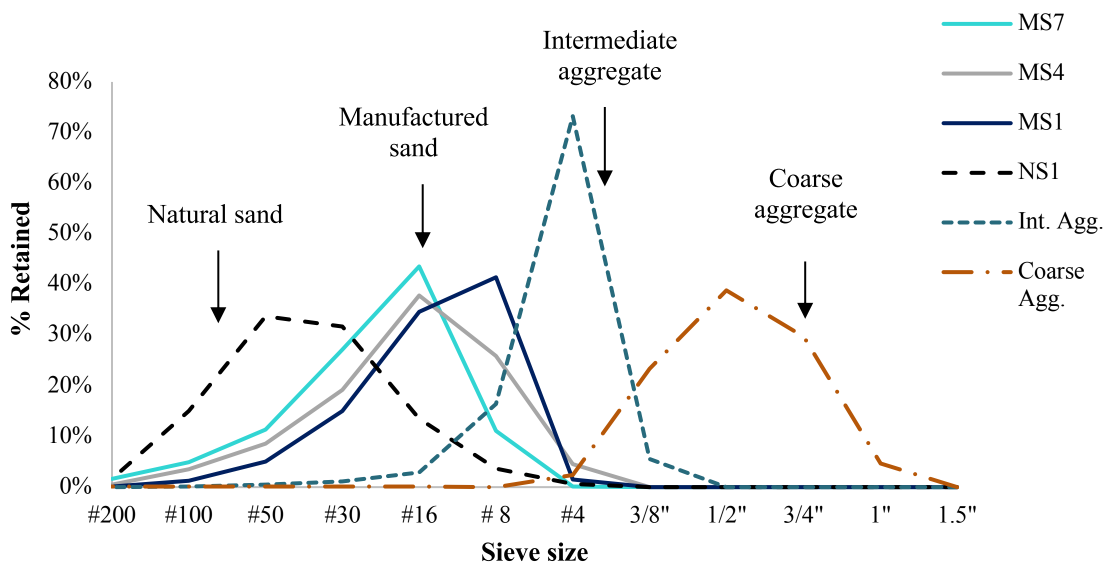


Figure 4- 2 Aggregate gradation for the materials used in the study.

4.3.2 Shape properties of manufactured sand

In this study, the Uncompacted Voids Content Method A (ASTM C1252) was used to quantify the shape of the sands as it has been shown to correlate well to visual observations as well as the angularity and shape as measured by the AIMS II [48]. The combined uncompacted voids content was used to express the shape properties of a blended fine aggregate (natural sand and manufactured sand) via the equation [48] below:

$$\text{Voids content of the combined fine aggregates} = \frac{100}{\frac{P1}{\text{voids content 1}} + \frac{P2}{\text{Voids content 2}}} \quad \textbf{(eq. 8)}$$

Where,

P1: weight percentage of the natural sand

P2: weight percentage of the manufactured sand

Voids content 1: uncompacted voids content of the natural sand

Voids content 2: uncompacted voids content of the manufactured sand

4.3.3 Mixture design

4.3.3.1 Concrete mixture design

The coarse aggregates for this work had a constant gradation. In contrast, the gradation of the fine aggregate was variable based on the volume of manufactured that replaced the natural sand in a mixture. This was due to the coarseness of the manufactured sand gradations. The manufactured sands replaced the natural sand by volume of the fine aggregate in an incremental manner so that variable fine sand contents could be obtained: within the limits, at the limit, and below the 25% limit identified by the Tarantula Curve. The control mixture design is shown in Table 4-3. The combined gradations for the different mixtures are shown in Fig. 4-3 on the Tarantula Curve.

Table 4- 3. Mixture Design for the Control Mixture

<table>
<tr><th>Material</th><th>Weight (lbs/yd3)</th><th>Mass (kg/m3)</th><th>Volume (%)</th></tr>
<tr><td>Coarse Aggregate</td><td>1350</td><td>801</td><td>30</td></tr>
<tr><td>Intermediate Aggregate</td><td>515</td><td>306</td><td>11</td></tr>
<tr><td>Natural Sand</td><td>1280*</td><td>759*</td><td rowspan="2">30</td></tr>
<tr><td>Manufactured Sand</td><td>Varied</td><td>Varied</td></tr>
<tr><td>Cement</td><td>489</td><td>290</td><td rowspan="4">29</td></tr>
<tr><td>Fly ash</td><td>122</td><td>73</td></tr>
<tr><td>Water</td><td>275</td><td>163</td></tr>
<tr><td>WR</td><td>6 oz./cwt</td><td>3.5 ml/kg</td></tr>
</table>

* These are the values with no manufactured sand added.

Note that from previous work done by Seader, the fine sand contents of mixtures with natural sand only were varied by reducing the fine aggregate volume [50]. Table 4-4 shows the different aggregate proportions of mixtures with natural sand only.

Table 4- 4. Mixture Proportions with Natural Sand Only [50]

Mixture ID	Paste	Coarse Aggregate	Intermediate Aggregate	Natural sand (NS1)
C-07	29%	32%	16%	23%
C-08	29%	29%	14%	27%
C-09	29%	28%	13%	29%

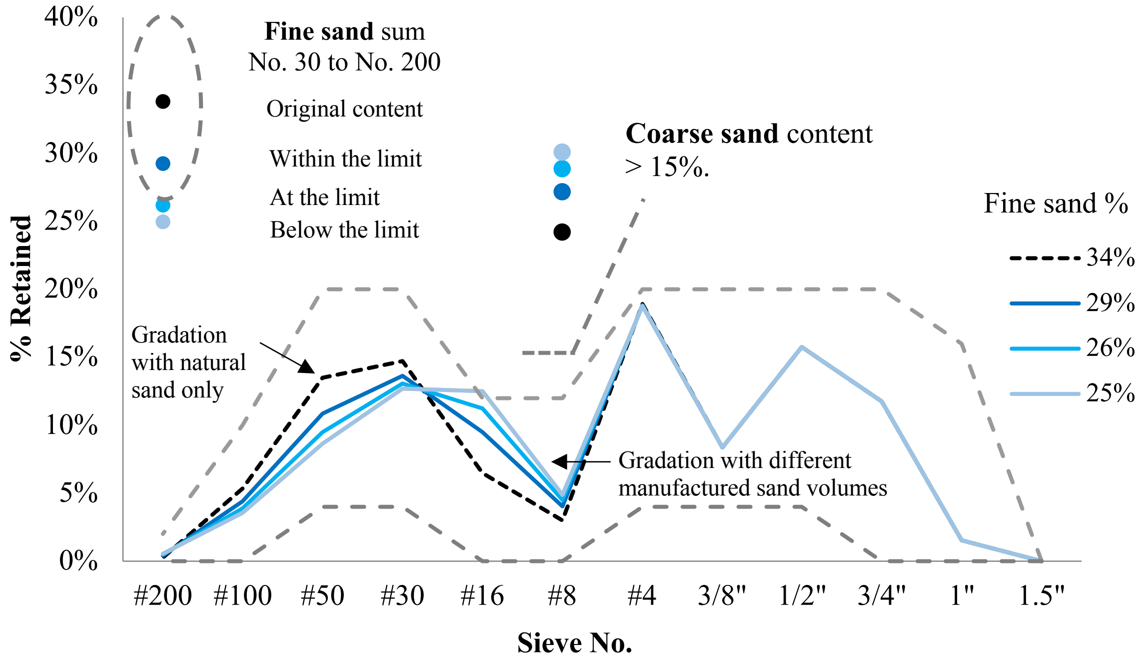


Figure 4- 3 plots an example of combined gradation changes in the control mixture due to the incremental replacement of the manufactured sand (MS7) to the natural sand (NS1).

4.3.3.2 Grout mixture design

The pump and pipe network were primed with grout prior to each pumping session. Priming consists of lining the walls of the pump and pipe network with a thin lubricating layer of mortar. The grout mixture used a Type 1 cement, meeting the requirements of ASTM C150, with a w/cm of 0.40, 597 kg/m^3 (1006 lbs/yd^3) of cement, and 1491 kg/m^3 (2514 lbs/yd^3) of sand from the same natural sand used in the concrete mixtures.

4.3.4 Pumping equipment

4.3.4.1 Concrete pump

A Putzmeister TK50 pump was used in this study for concrete testing. It has a 0.14 m^3 (5 ft^3) hopper with two cylinders to draw concrete from the hopper and two pistons that push the drawn concrete through the pipeline network via an S-valve. The S-valve switches between the two cylinders allowing the piston full of concrete to push it through the pipeline while the recently empty piston to draw concrete from the hopper. This mechanism will provide an approximately continuous flow of concrete. The pump was set on the maximum piston volume of 0.016 m^3 (0.57 ft^3) and engine revolution per minute (rpm) of 1500 rpm, as determined by previous work, to obtain consistent measurements [50].

4.3.4.2 Pipeline configuration

A standard pipeline configuration was used in this work. Single wall steel pipes with an internal diameter of 10 cm (4 in.) were used. Also, rubber gaskets and couplings were used to secure the pipe sections together. The pipeline had a 16.6 m (55.9 ft) in length with a 3 m (9.8 ft) rubber hose at the end of the pipe network. Since the output diameter of the pump is 13 cm (5 in.), a 1 m (3.3 ft) long reducer pipe was required to make the transition in the internal diameter from 13 cm to 10 cm (5 in. to 4 in.). The network has three 90° bends with a radius of 0.5 m (1.5 ft). Note that the rubber hose was used to allow recirculating the concrete while testing, also, discharging the concrete after the pumping session was over. The layout of the pipe network is shown in Fig. 4-4.

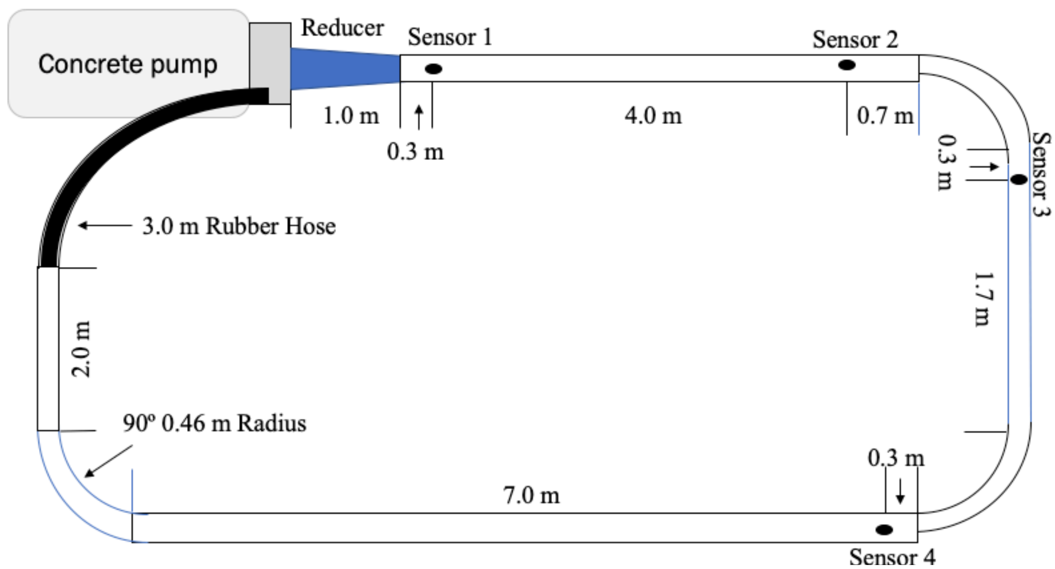


Figure 4- 4 illustrates an overview of the pump pipe network.

4.3.4.3 Pressure sensors

The pressures induced by pumping concrete in a pipeline system were measured via a novel pressure sensor arrangement developed by Feyes [50]. In this arrangement, GE 5000 pressure sensors were used to measure pumping pressures in the pipeline, which are capable of measuring pressures between – 100 to 3495 kpa (-14.5 to 507 psi) with +/- 3 kpa (+/-0.5 psi). The pressure sensors were located at different spots to measure the loss of pressure through the pipe network. Sensor 1 was located right after the reducer to measure the output pressures. Next, sensor 2 was put before the first 90° bend and 4 m (13.1 ft) away from sensor 1. Sensor 3 was located right after the first 90° bend to measure the loss in the pressure due to the 90° bend between sensor 2 and sensor 3. Sensor 4 was located immediately after the second 90° bend, which could be used with sensor 3 to measure the loss of the pressure due to the second bend. These locations of the sensors are shown in Fig. 4-4. More details about the sensors can be found in the appendix.

4.3.5 Material preparation and mixing procedure

The aggregates were collected from the stockpiles and brought into a temperature-controlled laboratory room at 73 °F for a minimum period of 24 hours before mixing. Then, the aggregates were placed in a mixing drum and spun to take representative samples for a moisture correction. At the time of mixing, all coarse and fine aggregates were loaded in the mixer along with 2/3 of the water content and mixed for three minutes to make the mixed materials to be homogeneous and approach the saturated surface dry condition (SSD). Subsequently, the cementitious materials were added along with the remaining water and mixed for three minutes. The produced mixture rested for two minutes, and the sides of the mixer were scraped. After the rest period, the admixtures were added, and the concrete was mixed for another three more minutes.

Note that the size of the grout mixture was 0.11 m^3 (4 $ft^{3)}$, while the concrete mixtures had a total size of 0.43 m^3 (15 ft^3). The concrete mixture was prepared in three 0.14 m^3 (5 ft^3) batches. The purpose of the grout mixture was to lubricate the pipeline to facilitate the concrete movement while the 0.43 m^3 (15 ft^3) of concrete was required to provide enough material to maintain concrete flow and samples for concrete testing.

4.3.6 Pumping procedure

A grout mixture with a typical slump value around 210 mm (8.25 in.) was used to create a lubricating mortar layer around pipes to minimize friction in the line and segregation. First, the grout was added in the hopper, and a few strokes were made at 1500 rpm to push the grout into the pipeline and lower the hopper level. Then, the concrete was transferred to the hopper. Note that as the pump was running, the end of the rubber hose was placed in an empty barrel to collect the grout. Once the concrete started to exit the rubber hose, the pump was stopped. Then, the rubber hose was moved back to the hopper to recirculate the concrete. The pump was turned on again for at least ten piston strokes at 1500 rpm to illuminate any air gaps that could have occurred during placing the concrete in the hopper. After the air gap removal stage was done, the concrete testing was started by taking a sample, and the time was set as 0 minutes.

4.3.6.1 Concrete sampling

To obtain a concrete sample, the pump was stopped, and the rubber hose was disconnected from the hopper and moved to a plastic bin. Then, by holding the rubber hose over the plastic bin, the pump was turned on, and two-piston strokes were made to collect concrete for testing.

4.3.6.2 Concrete workability testing

As part of the testing procedure to determine the impact of the manufactured sand on the concrete pumpability, a workability performance scale, developed by Cook, was used to indicate the workability performance at each fine sand content of the tested mixtures. It consists of the ICAR Rheometer test [45] along with the Slump test [43] and the visual observation [32]. More details can be found in Cook. Table 4-5 shows the workability performance scale. This scale will be used to compare the pumping pressures to the workability performance of the mixtures.

Table 4- 5. Performance Scale for Concrete Workability (modified from Cook [32])

Workability Performance Scale for Each Test	**Slump Test** (mm)	**Visual Observation**	**ICAR RHEOMETER**		
			Static Yield Stress (pa)	Dynamic Yield Stress (pa)	Plastic Viscosity (pa/sec)
Excellent (1)	203 to 152	1	<1000	<250	<10
Good (2)	152 to 102	1 to 2	1000-1500	250-500	10 to 15
Moderate (3)	102 to 51	2 to 3	1500-2000	500-1000	15 to 20
Poor (4)	51 to 0	3 to 4	>2000	>1000	>25
Unusable (5)	0	4 to 5	Too stiff	Too Stiff	Too Stiff

4.3.6.3 Concrete pumping session

As mentioned earlier, the pump was set at 1500 rpm, and ten pistons stokes were made to illuminate the air gaps due to moving the concrete in the hopper. Next, the first sample was taken to conduct the Slump Test and the ICAR Rheometer Test, and the time was set to be 0 minutes. Note that the ICAR Rheometer test takes about 45 seconds per test, and it had to be done multiple times to obtain accurate data [50]. Therefore, each testing interval was estimated to be 15 minutes. This means that a sample was collected after circulating the concrete and then every 15 minutes until a slump of 76 mm (3.0 in.) was reached.

After the concrete sample was taken, the rubber hose was placed back into the hopper, and the pump was run at 1500 rpm for 30 piston strokes, then, it was run at 1200 rpm for 30 piston strokes. Then, the rpm was increased to 1500, and the pump was kept running until the next testing interval. This pumping cycle scheme, shown in Fig. 4-5, was established by preliminary work, done by Seader, to ensure that the pump has sufficient energy to prevent seizing when the mixture gets stiffer and prevent the pump engine from overheating [50].

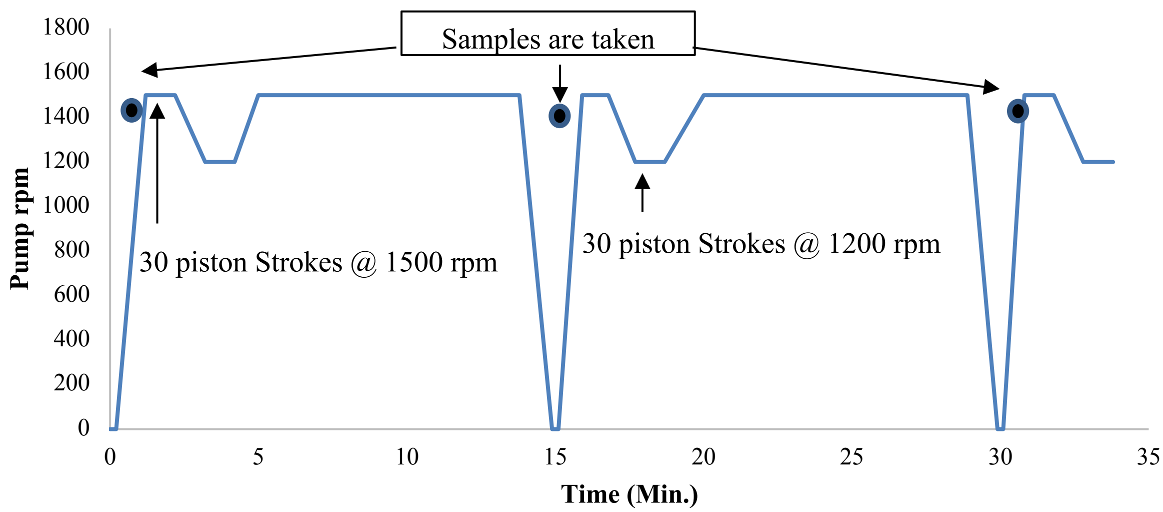


Figure 4- 5 shows a typical pump cycle that occurred at each testing interval.

Note that a mixture is considered "too stiff" if it requires more than 1500 rpm to keep pumping. It typically occurs when pumping mixtures with low workability in which it will require high pressures to move the concrete inside the pipelines, which corresponds to poor pumping performance [50]. Also, one can investigate the concrete discharged at the end of the pipe for any segregation. For example, if only aggregates were exiting the hose with no mortar, then the concrete segregated, and this will cause the pipeline to be blocked. This would not be acceptable in the field, and the mixture would be considered as a failure and is labeled as segregated [50].

4.3.7 Pressure sensor output

After the concrete pumping was done, the data from each sensor were retrieved and analyzed to produce a pressure curve for each sensor. Fig. 4-6 shows a typical pressure curve generated by a piston stroke. Note that a piston stroke has a primary curve and a secondary curve. The primary curve is the initial pressure required to initiate movement in the concrete when the piston starts to move in the cylinder. The secondary pressure is the pressure necessary to maintain the mobility of the concrete while the piston is moving in the cylinder.

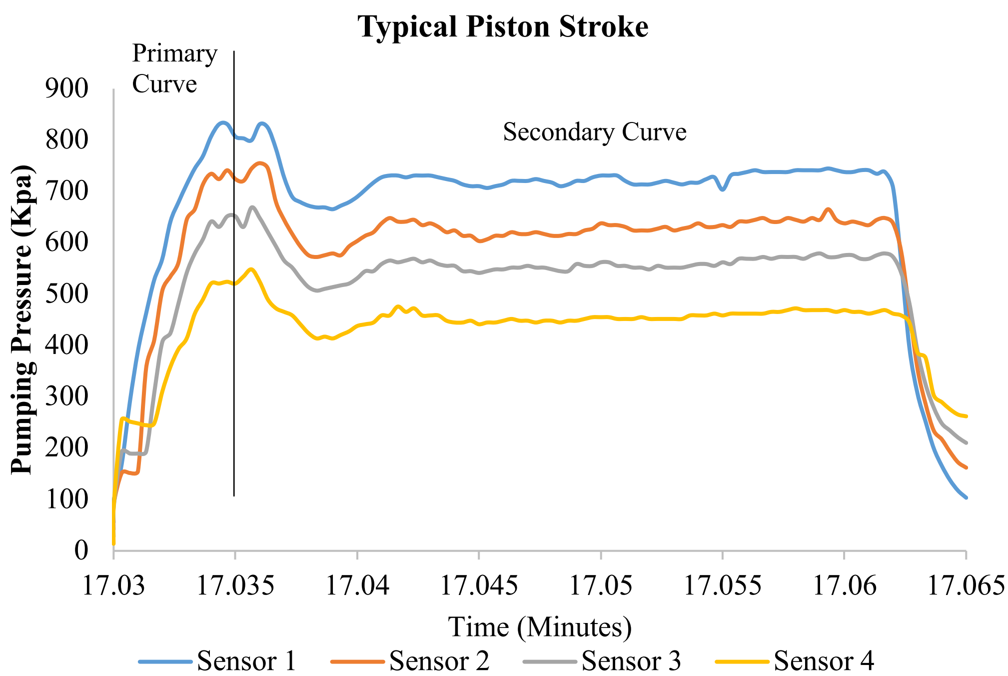


Figure 4- 6 shows a pumping pressure curve with a primary and a secondary curve.

A computer code developed by Seader was used for the pressure data analysis and producing the pressure curves for the sensors. The maximum value from the primary curve and the average value from the secondary curve with the coefficient of variation are used in the analysis. The details on how this self-authored computer code works can be found in Seader [50].

4.3.7.1 Secondary curve average pressures

This work used the average secondary pressure, obtained from the center 70% of the measurements on the secondary curve to characterize each mixture. In this work, the typical coefficient of variation (COV) was 2% while the range was from 0.2% to 10%. To determine the average secondary pressure at different sampling time, the average secondary pressure from the last 10 full piston strokes before sampling were averaged. This allowed the comparison of the average secondary pressures between mixtures. Note that the COV between the average secondary pressure of the last 10 strokes was always less than 10%.

These measurements were made at 0, 15, and 30 minutes after the pumping session started. Recall that an average secondary pressure of 414 kpa (60 psi) for sensor 2 was set as a conservative estimate where a concrete mixture to be considered undesirable for pumping purposes because of poor workability. This 414 kpa (60 psi) pressure limit corresponds to a 25% increase from the initial pumping pressure for well-performing mixtures, and it is typically translated to a low workability mixture [50].

4.4 Results and discussion

4.4.1 Concrete mixtures evaluation

The workability performance scale was used to evaluate the workability of the concrete mixture with manufactured sand. Detailed results can be found within the appendix. To measure the effect of replacing the natural sand with manufactured sand on the pumpability performance, the average secondary pressures of the concrete mixtures at 0, 15, and 30 minutes were measured. Recall that if the average secondary pressure was higher than 414 kpa (60 psi) for sensor 2, then, the concrete mixture to be considered undesirable for pumping purposes.

4.4.2 Comparing workability performance to pumping pressures

In this section, comparisons between the average secondary pressures versus the slump and ICAR Rheometer performance of the concrete mixtures were made. This was done to evaluate how these parameters correlate with each other.

4.4.2.1 Slump and pump pressure

The slump and the average secondary pressure data at each time interval were measured and plotted in Fig. 4-7 with a best-fit line. Based on Fig. 4-7, as the slump increased, meaning that the concrete can be more flowable, the pressure required to pump the concrete decreased. It can be noted that for sensor 1 through sensor 3, the pressure in the pump line correlated relatively strong with the slump. Also, a similar slope can be seen for each sensor even though the pressure decreased as the concrete flowed through the pump line. This suggests a linear relationship between the change in the pumping pressure and the change in the slump. This linear relationship occurred regardless of the pump line distance or the bends in the line before a particular location. This supports the work done by Searder with natural sands [50].

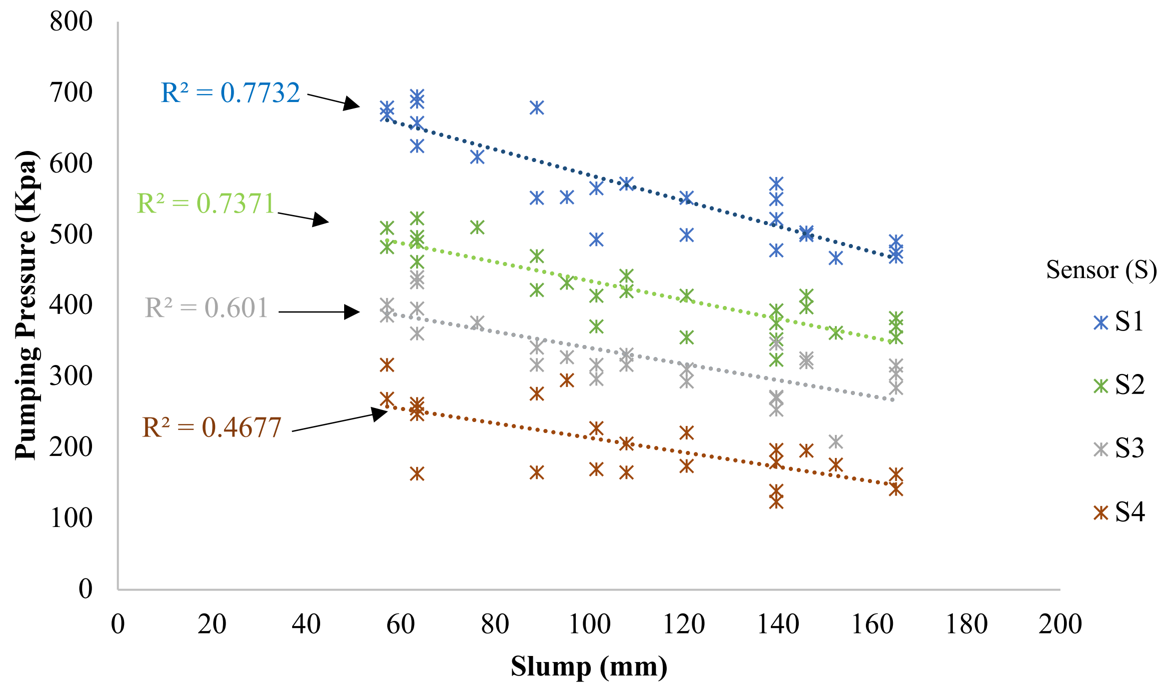


Figure 4- 7 shows slump data versus pumping pressures.

One can note that sensor 4, located after the second 90° bend has more scattered data, which reflected on the correlation to be less in comparison to the other sensors. This could be caused by factors such as the lower pumping pressure due to the further distance from the pump and the bends in the pump line. Also, the friction in the pipeline could cause this scatter in the data [50].

4.4.2.2 ICAR Rheometer and pump pressure

Another correlation between the average secondary pressures and the workability performance can be made by plotting the pressure data on the Y-axis and the ICAR Rheometer (static and the dynamic stresses) on the X-axis. Fig. 4-8 shows sensor 2 pressures versus the Rheometer Static and dynamic yield stresses; more plots are shown in the appendix. Note that these plots closely match the charts developed by Seader for mixtures with natural sand only in which as rheometer yield stresses (static and dynamic) increased, the pressure in the pump line increased as well. This is true because higher yields stresses indicate that the concrete is hard to flow, which yields higher pumping pressures to force the concrete to flow through the pump line. Those charts show a reasonably acceptable correlation between the rheometer yield stresses and the pumping pressures.

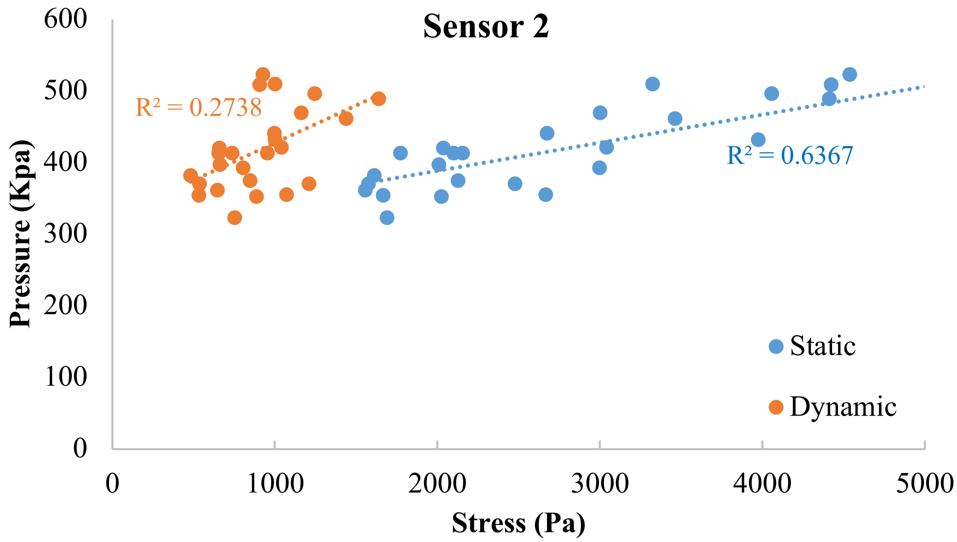


Figure 4- 8 plots sensor 2 pressures at 1500 rpm versus the rheometer yield stresses (static and dynamic).

4.4.3 Fine sand content range for pumpable concrete

The purpose of this study was to investigate the impact of the manufactured sand on the concrete pumpability performance. In this work, the fine sand contents of mixtures with variable amounts of manufactured sand will be compared to the workability performance and the average secondary pressures of those mixtures.

4.4.3.1 Comparing workability performance to fine sand contents

Previous research showed that the fine sand content in a combined aggregate gradation has an impact on the workability performance. The reduction in the fine sand content, due to the increase in the manufactured sand volume, can decrease the workability performance [48]. This caused the Rheometer yield stresses (Static and dynamic) to increase and the slump to decrease. More details are shown in the appendix. The results showed similar trends to the previous work done by Seader for mixtures with natural sand only.

4.4.3.2 Comparing pumping pressures to fine sand contents

To investigate the effects of the fine sand content on the concrete pumping pressure, Fig. 4-9 plots the mixtures using the fine sand contents, the pressures from sensor 2 at 0 minutes, the combined uncompacted voids contents, and the replacement levels of manufactured sand. Note that each line represents mixtures made with a manufactured sand source. The color of the dots on each line changes based on the pressure amount, and the range of manufactured sand replacement by volume is shown numerically for each series of data points for fixed fine sand content.

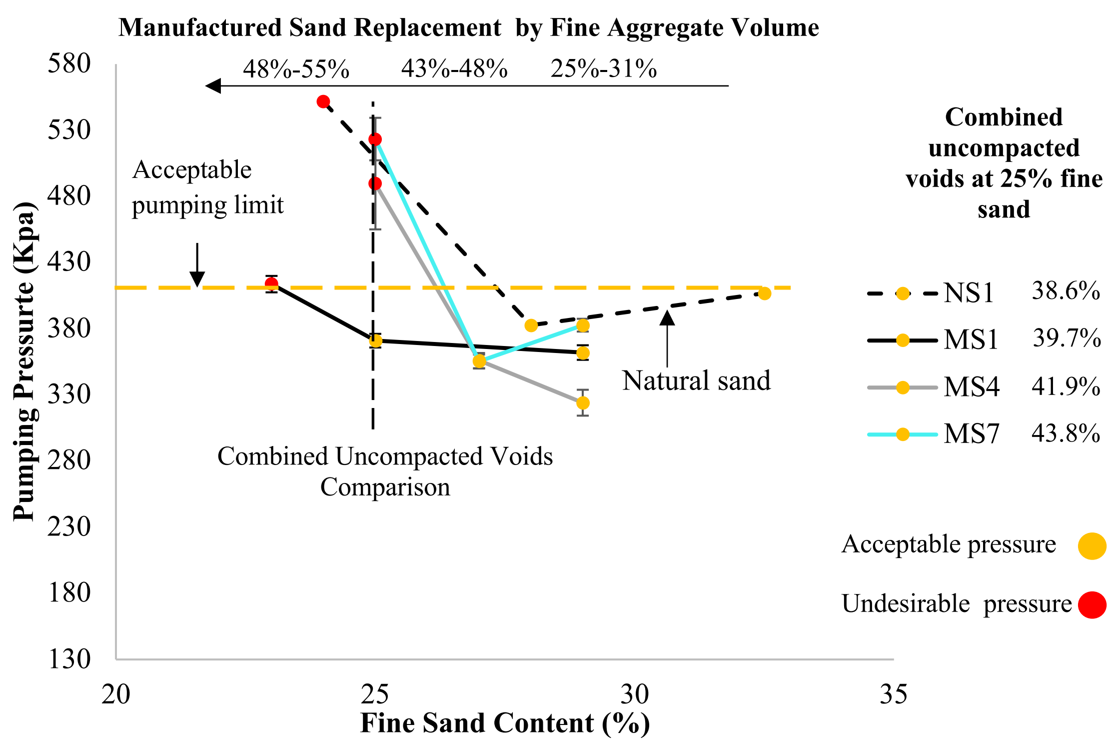


Figure 4- 9 shows sensor 2 pressures at 0 min. versus the fine sand contents.

Fig. 4-9 shows that as the fine sand content decreased, the pumping pressures increased. Note that the reduction in the fine sand volume coincided with an increase in the manufactured sand replacement level. This occurred because the gradation of the manufactured sand was coarser in comparison to the natural sand.

Mixtures with natural sand only (NS1) from previous testing [6] were also plotted in Fig. 4-9. Note how reducing the fine sand volume in these mixtures resulted in higher and undesirable pumping pressures. Note that the reduction in the fine sand volumes of these mixtures coincided with a reduction in the fine aggregate volume percentage of the total mixture volume.

Therefore, in both cases, the reduction in the fine sand content in a combined aggregate gradation of a mixture can cause the pumping pressure to increase. Thus, the fine sand content in a combined aggregate gradation played a significant role in the concrete pumping pressure performance.

One can notice that as the manufactured sand replacement level went up or as the fine sand content decreased, the combined uncompacted voids content increased. In contrast, for mixtures with natural sand only, as the fine sand content decreased, the uncompacted voids content stayed constant.

The impact of the particle shape, expressed in the combined uncompacted voids content, is easiest to observe at 25% as there is a significant difference in the pumping pressure. The mixture with manufactured sand with the lowest uncompacted voids content (MS1 with 39.7%) showed lower pumping pressure, and all other manufactured sands had high pressures (>414 kpa (60 psi)). This suggests the significance of the uncompacted voids content of the blended fine aggregates as they can impact the pumping pressures.

This work showed that the manufactured sand can be used in the range between 43 and 48% replacement of the natural sand and still achieve acceptable pumping pressures, less than 414 kpa (60 psi). However, when the replacement levels are higher, >48%, then the pumping pressures increase and become undesirable.

It is important to emphasize that the replacement level of the manufactured sand is not always an acceptable method to estimate pumpability performance. However, it is highly recommended to use the Tarantula Curve with the combined gradation limits with a particular focus on the fine sand content in the combined aggregate gradation.

Fig. 4-10 helps to show the relationship between the fine sand content and the combined uncompacted voids content. The pumping pressures from these mixtures are indicated by different colors for the data points that represent if the mixture had an acceptable pumping pressure.

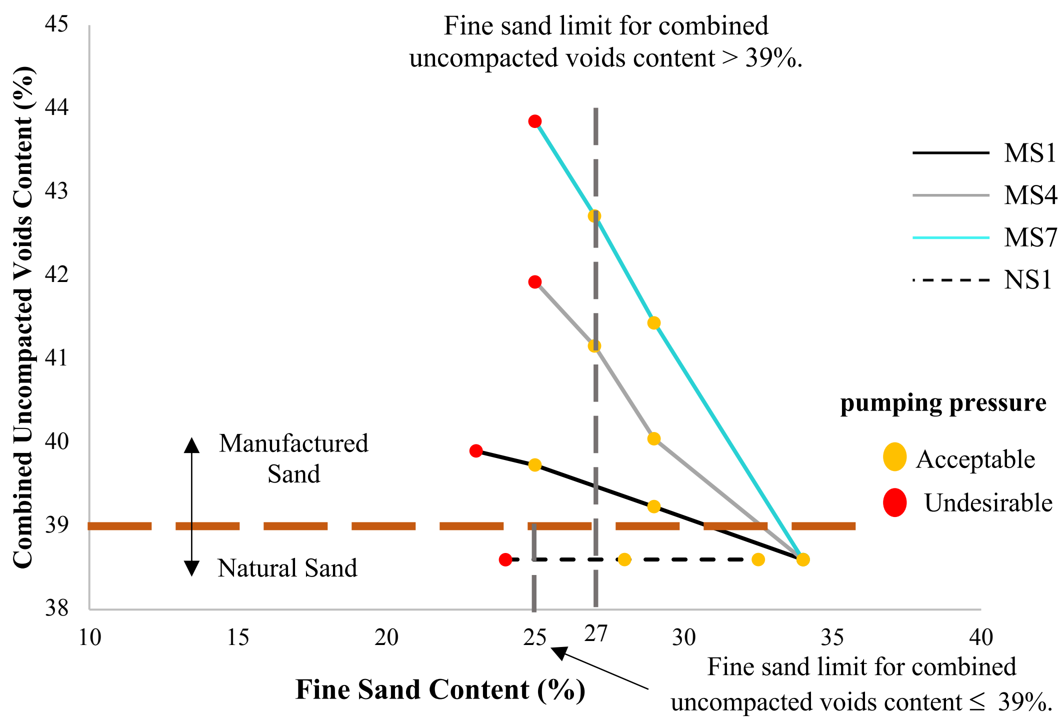


Figure 4- 10 plots sensor 2 pumping pressure at 0 min. versus different fine sand volumes and combined uncompacted voids contents.

Fig. 4-10 matches the adjusted fine sand content boundaries shown in Fig. 4-1, and it is shown again below in Fig. 4-11. For a combined uncompacted voids content of blended fine aggregates > 39%, the minimum fine sand content limit is 27%. However, for a combined uncompacted voids content ≤ 39% of fine aggregates (mixtures with natural sand only), it is recommended to use a fine sand content limit of 25% [50]. This work agreed with other work where satisfactory pumpable mixtures with a blend of manufactured sand and natural sand can be achieved [16]

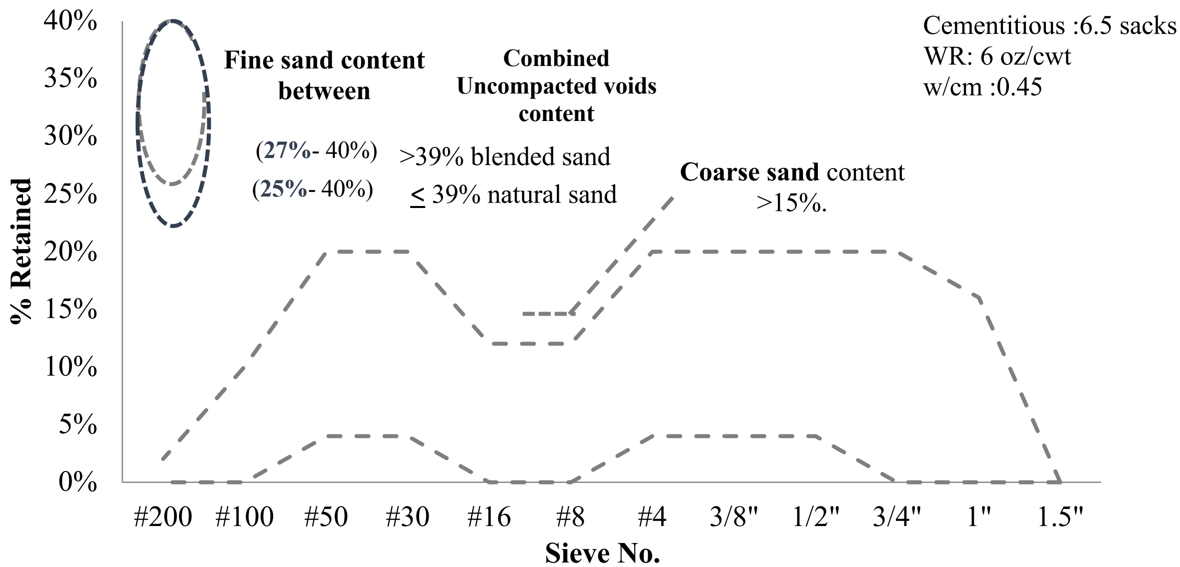


Figure 4- 11 shows the modified Tarantula Curve limits for both the sieve sizes and the fine sand and coarse sand volumes to proportion aggregates.

4.5 Practical significance of this study

Substituting natural sand with manufactured sand in concrete has started to be a trend in concrete industry. However, challenges could be faced when using this kind of materials as they can reduce the workability. Due to the little published guidance on a technique for proportioning the manufactured sand in a pumpable concrete mixture, this research provides a simple and practical approach to design pumpable concrete mixtures with manufactured sands. Mixtures were made and pumped with manufactured sands to determine their performance. It was found that the fine sand content was the most critical parameter in assessing the pumpability of the mixtures, and the modified limits for the Tarantula Curve are suggested for pumping.

This work shows that successful and pumpable concrete can be produced by following the modified guidelines for the Tarantula Curve by replacing 45% of the natural sand with manufactured sand. However, this percentage is not constant for every source, and the acceptable replacement level should be determined by the fine sand content and the uncompacted voids content in the mixture. Based on the tested mixtures in this work, when the combined uncompacted voids content of the fine aggregates (manufactured sand and natural sand) is > 39%, the minimum recommended fine sand content limit is 27%.

Note that higher replacement levels of manufactured sand may be able to be used if the paste content, water to cement ratio, or admixture dosage is modified. This is an area of future study.

4.6 Conclusion

This work investigates how the manufactured sand impacts the pumpability of concrete through an increase in line pressure and also segregation. This work shows the importance of the fine sand volume (sum of No. 30 – No. 200) and also the combined uncompacted voids content. Both parameters are impacted as the replacement level of manufactured sand increases in a concrete mixture. It is essential to know that the manufactured sands used in this study were washed, meaning that the fines were less than the ASTM C 33 limit of 7%. In this work, the fines ranged between 2.59% and 0.70%. A modification to the Tarantula Curve for mixtures with manufactured sand is recommended.

The following were necessary to ensure the concrete mixtures had acceptable pumping pressures:

- The sum of No. 30 – No. 200 or a fine sand content > 27% is recommended when the uncompacted voids content is > 39%. This occurs with blends of manufactured sands and natural sands.
- A minimum fine sand content limit of 25% is recommended when the uncompacted voids content is < 39%. This typically occurs when using natural sands.

This work provides guidance on how to produce workable and pumpable concrete mixtures that contain manufactured sand. This is an essential step in producing satisfactory pumpable concrete.

CHAPTER V

CONCLUSION

The primary goal of this research was to investigate the impact of substituting the natural sand with manufactured sand on the flowable concrete performance. This work also provided a practical and straightforward concrete design method that can proportion the manufactured sand along with the other aggregates in a mixture. This dissertation was composed of three studies to investigate the manufactured sand impacts on concrete performance. The first study quantified the shape properties of manufactured sands and natural sands using sophisticated tests such as the AIMS II and more practical lab tests such as the Uncompacted Voids Content (ASTM C1257 - Method A). It also investigated the impact of incorporating the manufactured sand in concrete as another source of fine aggregates. The second study investigated the effect of the paste content on proportioning the manufactured sand in concrete. The third study evaluated the impacts of the manufactured sand on the pumpability performance of mixtures containing manufactured sand.

The following conclusions were drawn from **Chapter II**.

- A linear correlation with R-squared value ≥ 0.80 was made between the Angularity Index, Form Index, and uncompacted voids content percentage measurements from the AIMS II and the uncompacted void content (ASTM C 1252-Method A).

- A combined uncompacted voids content limit of 39% was able to differentiate between manufactured sand and natural sand.
- When blending manufactured sand sources with similar gradation, the workability decreased as the combined uncompacted voids content increased.
- The fine sand content (sum of No. 30 - No. 200) was critical in determining the amount of manufactured sand used in a concrete mixture.
- A minimum fine sand content of 27% was recommended when the uncompacted voids content is >39% or when using blends of manufactured sand and natural sand.
- A minimum fine sand content of 25% was recommended when the uncompacted voids content is $\leq$ 39% or when using natural sands.
- The compressive strength increased as the fine sand content decreased. This trend continued until the workability of the mixture started to decrease. Once the workability decreased, then so did the compressive strength.
- This work provided guidance on producing workable and finishable concrete mixtures that contain manufactured sand for flatwork applications.

The following conclusions were drawn from **Chapter III**

The manufactured sand was proportioned in concrete using the Tarantula Curve. This work was primarily focused on how the paste volume used in a concrete mixture could allow more manufactured sand to be blended in a mixture. As the manufactured sand content increased in a concrete mixture, the fine sand content decreased, and the coarse sand content increased because the manufactured sand had coarse gradations. The impact of the angularity of the manufactured sand was expressed in the combined uncompacted voids content. The following were key highlights for the results:

- The paste volume in a mixture impacted the minimum required fine sand content to achieve acceptable workability, and so the allowable amount of manufactured sand in the mixture.
- There was a linear relationship between the allowable minimum fine sand content and the paste volume in the mixture. For a paste volume of 26.2% and 32.8%, the minimum fine sand content was 30% and 19%, respectively.
- For a paste volume of 32.8%, the allowable limit on the No. 8 and No. 16 sieve was 14% to control finishability problems.

The following conclusions were drawn from **Chapter IV**

This work investigated how the manufactured sand impacts the pumpability of concrete through an increase in line pressure and also segregation. Further, the importance of the fine sand volume (sum of No. 30 – No. 200) and also the combined uncompacted voids content was shown. Both parameters are impacted as the replacement level of manufactured sand increases in a concrete mixture. A modification to the Tarantula Curve for mixtures with manufactured sand was recommended.

The following were necessary to ensure the concrete mixtures had acceptable pumping pressures:

- The sum of No. 30 – No. 200 or a fine sand content > 27% was recommended when the uncompacted voids content is > 39%. This occurred with blends of manufactured sands and natural sands.
- A minimum fine sand content limit of 25% was recommended when the uncompacted voids content is < 39%. This typically occurred when using natural sands.

This work provided guidance on how to produce workable and pumpable concrete mixtures that contain manufactured sand. This was an essential step in making satisfactory pumpable concrete.

REFERENCES

[1] Taylor PC, Dam T., Sutter L., and Fick G. Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual. 2nd reprint. Washington, DC: FHWA; 2019.

[2] Aggregate Production Analysis. Pit & Quarry, <https://www.pitandquarry.com/2017-aggregate-production-analysis/> (Jul. 3, 2020); 2017

[3] Pilegis, M., Gardner, D., and Lark, R.. An Investigation into the Use of Manufactured Sand as a 100% Replacement for Fine Aggregate in Concrete. Materials; 2016, 9(6), 440.

[4] Siddiqui, M. A Rational and Sustainable Approach to Pavement Concrete Mixture Design. The University of Texas; 2014

[5] Supekar V. Properties of Concrete By Replacement Of Natural Sand With Artificial Sand. International Journal of Engineering Research & Technology; 2012.

[6] Alturki, R., Qualitative Evaluation in the Box Test and Evaluation of Field Mixtures by the Tarantula Curve. Master of Science thesis, Civil and Environmental Engineering, Oklahoma State University, Stillwater, United States; 2016.

[7] Folliard, K.J., and K.D. Smith. Aggregate Tests for Portland Cement Concrete Pavements Review and Recommendations. National Cooperative Highway Research Program, Research Report No. 281, Transportation Research Board of the National Academies, Washington, D.C.; 2003.

[8] Rached, M., David W., David P., and Fowler, D. Recommendations for Achieving Adequate Surface Friction and Predicting Skid Values in Class P Concrete Containing Manufactured Fine Aggregates. Research Report, Texas Department of Transportation, Research and Technology Implementation, Austin, TX.; 2012.

[9] Michael L., and Ufuk D. Effects of Manufactured Sands and Blended Aggregateson the Durability of Concrete Bridge Decks and Pavements. North Carolina Department of Transportation, Raleigh, North Carolina; 2008.

[10] Darwin, D., Browning, J., Lindquist, W., McLeod, H., Yuan, J., Toledo, M., and Reynolds, D.Low-Cracking, High-Performance Concrete Bridge Decks.Transportation Research Record: Journal of the Transportation Research Board; 2010, 2202(-1), 61–69.

[11] Mallela, J. et al. Measurement and Significance of the Coefficient of Thermal Expansion of Concrete in Rigid Pavement Design. Transportation Research Record: Journal of the Transportation Research Board; 2005, 38–46.

[12] Johansson, L. The Effect of Aggregate Grading and Mix Proportions on the Workability for Concrete Made with Entirely Crushed Aggregate. Studies on Concrete Technology, Swedish Cement and Concrete Research Institute; 1979, 147–160.

[25] Li, H. et al. Impact of Different Lithological Manufactured Sands on High-speed Railway Box Girder Concrete. Construction & Building Materials; 2020

[14] Choi, M. et al. Lubrication Layer Properties during Concrete Pumping. Cement and Concrete Research; 2013.

[15] Choi, M. S. Kim, Y. J. and Kwon, S. H. Prediction on Pipe Flow of Pumped Concrete Based on Shear-Induced Particle Migration. Cement and Concrete Research; 2013.

[16] Guoju, Ke, Wang, J., and Tian, Bo. Simulation Analysis of Pumping and Its Variability for Manufactured Sand Concrete. Aci Materials Journal. 116. 35-42; 2019

[17] Manning, D. Exploitation and Use of Quarry Fines; Report No: 087/MIST2/DACM/01; Mineral Solutions Limited: Manchester, UK; March; 2004.

[18] Marek, C.R. Importance of Fine Aggregate Shape and Grading on Properties of Concrete. In Proceedings of the International Center for Aggregates Research 3rd Annual Symposium, Austin, TX, USA; 1995.

[19] ASTM C 33. Standard Specification for Concrete Aggregates. West Conshohocken, PA: ASTM; 2013.

[20] Katz, A.& Baum, H.. Effect of High Levels of Fines Content on Concrete Properties. ACI Materials Journal; 2006,103. 474-482

[21] Lohani T.K.. Optimum utilization of quarry dust as partial replacement of sand in concrete. International Journal of Applied Science and Engineering Research; 2012.

[22] Hudson, B. P., Effect of Manufactured Aggregate and Sand Shape on Concrete Production and Placement. Svedala Barmac New Zealand Limited, Report; 1995

[23] ACI 211.1-91. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. ACI manual of concrete practice, Part 1, American Concrete Institute, Detroit, Mich, 38 pp; 2009.

[24] Saunders, C. H. Manufactured Sand Usage in North Carolina. Austin, TX; 1996.

[25] Koehler, E. P., and Fowler, D. W. Aggregates in Self-Consolidating Concrete. Research Report, International Center for Aggregates Research, The University of Texas at Austin, Austin, TX, 353; 2007.

[26] Quiroga, P. N., and Fowler, D. W. The Effects of Aggregates Characteristics on the Performance of Portland Cement Concrete. Research Report, International Center for Aggregates Research, The University of Texas at Austin, Austin, TX, 382; 2004.

[27] Rached, M., De Moya, M., and Fowler, D. W. Utilizing Aggregates Characteristics to Minimize Cement Content in Portland Cement Concrete. Research Report, International Center for Aggregates Research, The University of Texas at Austin, Austin, TX, 117; 2009.

[28] Shilstone Sr, J. M. Concrete Mixture Optimization. Concrete International; 1990, 12(6), pp. 33– 39.

[29] Andersen, P. J., and Johansen, V. Particle packing and concrete properties. Volume 43 of RH & H bulletin; 1993.

[30] Goltermann, P., and Johansen, V. Packing of Aggregates: an Alternative Tool to Determine the Optimal Aggregate Mix. ACI Materials Journal; 1997, 94(5), 435–442.

[31] Cook, D., Ghaeezah, A., Ley, T. and Russell, B. Investigation of Optimized Graded Concrete for Oklahoma-Phase 1. Oklahoma Department of Transportation, Oklahoma City, Oklahoma; 2013.

[32] Cook. D. Aggregate Proportioning for Slip Formed Pavements and Flowable Concrete, Oklahoma State University. Stillwater, OK; 2015.

[33] ASTM C 150. Standard Specification for Portland Cement. West Conshohocken, PA: ASTM; 2012.

[34] ASTM C 618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA: ASTM; 2012.

[35] ASTM C 494. Standard Specification for Chemical Admixtures for Concrete. West Conshohocken, PA: ASTM; 2005.

[36] ASTM C 136. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. West Conshohocken, PA: ASTM; 2014.

[37] Lindholm, R. A Practical Approach to Sedimentology. Dordrecht: Springer Netherlands; 1987.

[38] Little, D. et al. Quantify Shape, Angularity, and Surface Texture of Aggregate Using Image Analysis and Study Their Effect on Performance, tech., National Technical Information Service, Springfield, VA.; 2003.

[39] Masad, E. Aggregate Imaging System (AIMS): Basics and Application, tech., National Technical Information Service, Springfield, VA.; 2005

[40] ASTM C1252 Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading). West Conshohocken, PA: ASTM; 2017.

[41] Alger, Mark. S. M. Polymer Science Dictionary (2nd ed.). Springer Publishing; 1997.

[42] Askeland, R., Fulay, P., Wendelin J. The Science and Engineering of Materials (6th ed.); 2010.

[43] ASTM C 143. Standard Test Method for Slump of Hydraulic Cement Concrete. West Conshohocken, PA: ASTM; 2012.

[44] AASHTO TP137. Standard Method of Test for Box Test in Slip Form Paving of Fresh Portland Cement Concrete: AASHTO; 2020.

[45] Koehler, EP, Fowler, DW. Development of a Portable Rheometer for Fresh Portland Cement Concrete. ICAR Report 105-3. Austin, Tx: International Center of Aggregate Research; 2004.

[46] ASTM C 31. Standard Practice for making and Curing Concrete Test Specimens in the Field West Conshohocken, PA: ASTM; 2010.

[47] ASTM C39. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA: ASTM; 2008.

[48] Alturki, R., and Ley, T. Proportion Manufactured Sand in Concrete for Workability and Finishing. Unpublished manuscript, Civil and Environmental Engineering, Oklahoma State University, Stillwater, United States.

[49] Kosmatka, S. H., Wilson, M. L. Design and Control of Concrete Mixtures, 15th ed. Portland Cement Association. Portland, IL; 2011.

[50] Seader. N. Aggregate Proportioning for Slip Formed Pavements and Flowable Concrete, Oklahoma State University. Stillwater. OK; 2016.

APPENDICES

APPENDIX A

Chapter II

A1. Particle distribution

Table A 1. Particle Distribution of Manufactured Sand (MS) and Natural Sand (NS) Using Individual Percent Retained

sieve size	MS							NS	
	MS7	MS6	MS5	MS4	MS3	MS2	MS1	NS1	NS2
3/8"	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
No. 4	0.06%	4.53%	8.81%	8.81%	0.00%	0.47%	1.45%	0.63%	1.55%
# 8	11.14%	32.75%	39.97%	39.97%	9.08%	15.30%	41.43%	3.66%	6.36%
#16	43.57%	24.10%	30.35%	30.35%	37.09%	27.69%	34.65%	13.51%	15.57%
#30	27.21%	15.57%	13.65%	13.65%	24.80%	21.81%	15.06%	31.72%	32.01%
#50	11.31%	10.60%	5.04%	5.04%	16.29%	18.81%	5.04%	33.72%	32.36%
#100	4.88%	8.11%	1.57%	1.57%	10.14%	10.93%	1.25%	15.06%	9.59%
#200	1.70%	3.12%	0.33%	0.33%	1.52%	2.72%	0.17%	1.63%	2.51%
-#200	1.75%	1.21%	0.58%	2.59%	2.1%	3.85%	0.38%	0.27%	0.11%

A2. Float Test

The tools required to conduct the Float Test are shown in Figure A1.

(a) (b) (c) (d)

Figure A1 shows (a) dimensions of the Float test (Cook 2015), (b) template with three holes, (c) bull float, and (d) strike-off board.

The Float Test is conducted by making the following steps:

- The Float form is positioned on a level surface and slightly overfilled with freshly mixed concrete.
- The strike-off board is used to create a uniform surface and remove any excess materials. This is done by positioning the board on top of the concrete surface at one end and moving straight forward to the other end.
- Subsequently, fill with concrete some surface voids that might be created due to the striking off process.
- The template is used to create three standard holes with a depth and a diameter of 25 mm (1 in.).
- The modified bull float is placed on the concrete surface at one end and moved forward at a speed of 30 cm/sec. (0.5 ft./sec.). The speed can be measured by a metronome and pre-marked form side.
- The number of passes is counted in which a movement from one end to the other one is counted as one pass.
- The number of passes for closing the standard holes is counted as shown in Fig. A3
- The number of passes for obtaining a texture scale of 2 or lower is counted using Fig. A2
- After obtaining the numbers of passes for both finishability parameters,

a comparison is made with the performance scale shown in Table 4.

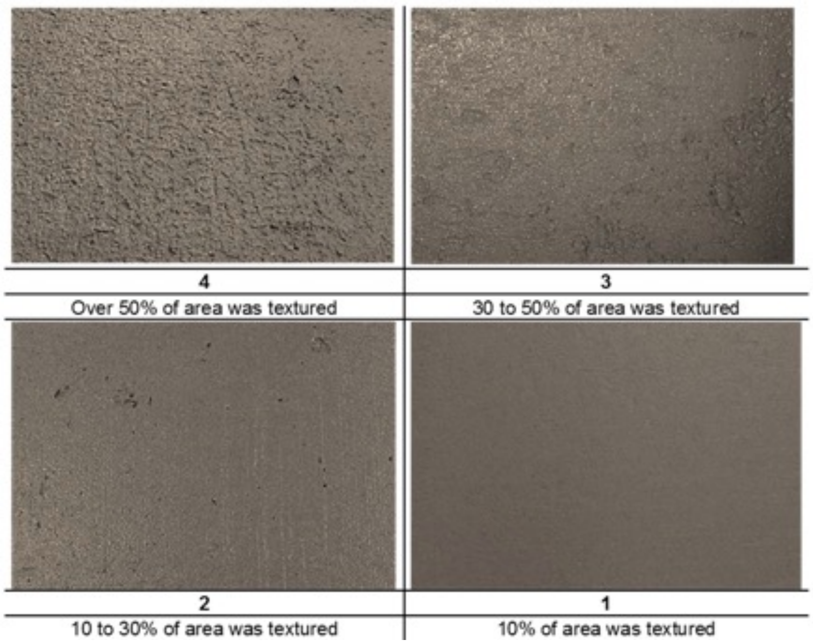


Figure A2 shows the Float Test ranking criteria (acquired from Cook 2015).

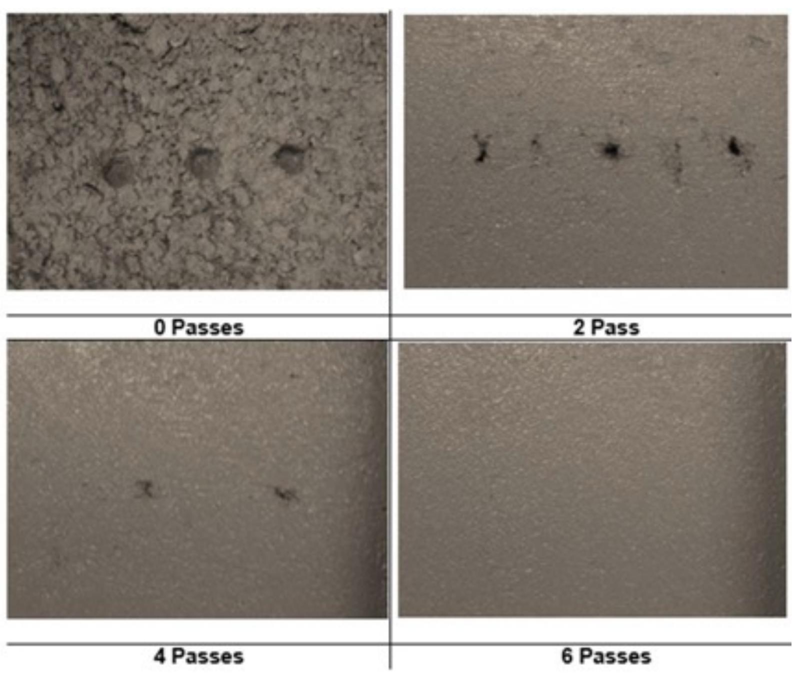


Figure A3 demonstrates an example of the number of passes required to close surface holes (acquired from Cook 2015).

A3. Visual observation

Each behavior listed in Table A2 is accompanied by a simple question, which an operator would use for the assessment to rank each behavior from 1 to 5. After determining the performance ranking for each category, an average ranking is determined by calculating the average numerical value obtained from each category and it is called the visual ranking performance.

Table A 2. Visual Observation Categories and Technique (acquired from Cook 2015)

Observation category	Visual inspection
Cohesion	Assessing the ability of the mixture to stay together **Laboratory Evaluation Method:** *Does this mixture segregate while mixing, discharging from the mixer, or setting in the wheelbarrow?* (1) Concrete mixture that has homogeneous compositions (2) Concrete mixture that is close to homogeneous (3) Concrete mixture that has minor amount of segregation while at rest, not at moving (4) Concrete mixture a large amount of segregation while at rest, but small amount of segregation while moving (5) Concrete mixture with an extreme amount of segregation while at rest or at motion
Richness	Assessing proportioned amount of sand and paste **Laboratory Evaluation Method:** *Will the paste and sand ratio content of the mixture be able to achieve proper flow and surface finishing requirements?* (1) Concrete mixture with a well-proportioned paste and sand amounts (2) Concrete mixture with good-proportioned paste and sand amounts (3) Concrete mixture with a moderate-proportioned paste and sand amounts (4) Concrete mixture with a poor-proportioned paste and sand amounts (5) Concrete mixture with an extremely poor-proportioned paste and sand amounts
Finishability	Assessing effort required to adequately finish the surface **Laboratory Evaluation Method:** *How difficult is it to float the surface of the concrete?* (1) Finishing surface of concrete did not take significant effort (2) Finishing surface of concrete took reasonable effort (3) Finishing surface of concrete took significant effort (4) Finishing surface of concrete took excessive effort (5) Finishing surface of concrete took unattainable effort
Flowability	Assessing effort required to continuously move the concrete **Laboratory Evaluation Method:** *How well does the concrete flow while mixing?* (1) Concrete mixture was flowing with insignificant effort (2) Concrete mixture was flowing with reasonable effort (3) Concrete mixture was flowing with significant effort (4) Concrete mixture was flowing with excessive effort (5) Concrete mixture was flowing with unattainable effort
Stiffness	Assessing effort required to initiate movement of the concrete **Laboratory Evaluation Method:** *How difficult is it to insert a hand scoop into the concrete?* (1) It took insignificant effort to start movement in the concrete (2) It took a reasonable effort to start movement in the concrete (3) It took significant effort to start movement in the concrete (4) It took excessive effort to start movement in the concrete (5) It took enormous effort to start movement in the concrete

Table A 3. The Use of Chi-Test to Sort the Angularity of the Particles of Different Sand Sources

Sand source	Angularity	Well rounded	Rounded	Sub rounded	Sub angular	Angular	Very Angularity	Sum	(M*F)/F	Sand Classification
	Range	5-6	4-5	3-4	2-3	1-2	0-1			
	Midpoint (M)	5.5	4.5	3.5	2.5	1.5	0.5			
NS1	Frequency (F)	7	8	2	3			21	5.5	Well-rounded
	Product (M*F)	38.5	44	11	16.5	0	0	115.5		
NS2	Frequency (F)	6	10	4	1			21	4.5	Rounded
	Product (M*F)	33	45	10.5	2.5	0	0	94.5		
MS1	Frequency (F)		5	6	7	3		21	3.1	Sub rounded
	Product (M*F)	0	22.5	21	15	4.5	0	65.5		
MS2	Frequency (F)		2	5	7	7		21	2.6	Sub angular
	Product (M*F)	0	9	17.5	17.5	9	0	54.5		
MS3	Frequency (F)		2	2	4	8	5	21	1.9	Angular
	Product (M*F)	0	9	7	10	12	2	40.5		
MS4	Frequency (F)			2	2	11	6	21	1.5	Angular
	Product (M*F)	0	0	7	5	16.5	2.5	31.5		
MS5	Frequency (F)				2	15	4	21	1.4	Angular
	Product (M*F)	0	0	0	5	22.5	1.5	29.5		
MS6	Frequency (F)				2	3	16	21	0.8	Very Angular
	Product (M*F)	0	0	0	5	3	8	17.5		
MS7	Frequency (F)					4	17	21	0.7	Very Angular
	Product (M*F)	0	0	0	0	4.5	8.5	14.5		

A4. Overall workability performance

Table A 4. Overall Workability Performance Results of the Concrete Mixtures

Fine sand	Blended manufactured sand	Combined Uncompacted voids content	Combined N0.200	Combined Fines	Overall workability performance	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (mm)	Float Test		Visual Observation	Compressive strength (Psi)	
										Hole	Texture		7-day	28-day
As-received gradation mixtures results														
30.6%	Original NS	38.6%	3.25%	0.80%	Good	1304	384	25	152	4	3	1.0	4872	6296
27%	MS2 (29%)	40.3%	2.18%	0.97%	Moderate	2169	564	19	152	7	6	2.0	5423	6994
	MS3 (29%)	40.4%	3.23%	1.04%	Moderate	1970	649	20	146	8	6	2.0	5501	6762
	MS4 (30%)	40.7%	2.21	1.02%	Moderate	1800	435	20	127	8	7	2.0	5197	5833
	MS6 (28%)	41.4%	3.21	0.88%	Moderate	1370	428	18	140	8	7	2.0	--	--
	MS7-1 (30%)	41.7%	2.53%	0.95%	Moderate	1791	369	28	159	8	7	2.0	5783	7440
25%	MS2 (40%)	40.9%	1.91%	1.07%	Poor	2262	769	25	146	8	7	2.6	4953	6397
	MS3 (41%)	41.0%	3.22%	1.19%	Poor	2714	816	23	140	8	9	2.6	5323	6660
	MS4 (43%)	41.4%	1.94%	1.14%	Poor	1938	807	27	121	11	9	2.2	5155	5950
	MS6 (36%)	41.9%	3.20%	0.91%	Poor	1507	457	27	127	10	12	2.2	--	--
	MS7-1 (42%)	42.8%	2.33%	1.03%	Poor	2500	683	27	108	12	10	2.4	5666	6931
23%	MS2 (50%)	41.4%	1.74%	1.16%	Unusable	2295	746	32	133	10	9	3.5	4716	6091
	MS3 (51%)	41.5%	3.21%	1.35%	Unusable	3211	920	30	127	9	10	2.8	5137	5828
	MS4 (53%)	42.0%	1.78%	1.26%	Unusable	3923	754	48	76	15	10	3.8	4996	5740
	MS6 (44%)	42.7%	3.19%	0.94%	Unusable	4100	750	43	108	13	11	3.5	--	--
	MS7-1 (51%)	43.7%	2.2%	1.09%	Unusable	4522	840	45	108	15	11	3.5	5400	6597

Table A4. (Continued)

Fine sand	Blended sieved sands	Combined uncompacted voids content	Combined No. 200	Combined Fines	Overall workability performance	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (mm)	Float Test		Visual Observation	Compressive strength (Psi)	
										Hole	Texture		7-day	28-day
Fixed gradation mixtures results														
30.6%	Original NS	38.6%	3.25%	0.80%	Good	1304	384	25	152	4	3	1.0	4872	6296
27%	NS1 (14%)	38.6%	1.04%	0.78%	Moderate	--	--	--	165	6	5	1.4	5291	6516
	NS2 (15%)	38.6%	0.98%	0.78%	Moderate	1436	485	20	178	5	5	1.4	5164	6118
	MS1 (16%)	39.3%	0.93%	0.78%	Moderate	--	--	--	140	5	4	1.4	5272	7331
	Blnd1 (15%)	39.4%	0.97%	0.78%	Moderate	1536	487	24	159	6	5	1.4	--	--
	Blnd2 (15%)	39.6%	0.97%	0.78%	Moderate	1629	656	20	127	7	6	2	--	--
	MS5 (15%)	39.9%	0.96%	0.78%	Moderate	1899	446	20	140	8	7	2.0	5167	6153
	MS7 (15%)	40.3%	0.96%	0.78%	Moderate	--	--	--	127	7	5	2.0	--	--
24%	NS1 (27%)	38.6%	0.63%	0.77%	Moderate	--	--	--	140	7	5	1.4	5194	7196
	NS2 (27%)	38.5%	0.63%	0.77%	Moderate	1816	499	20	127	6	6	2.0	5101	6875
	MS1 (31%)	39.5%	0.56%	0.77%	Moderate	1334	409	23	152	5	7	2.4	5259	6460
	Blnd1 (28%)	39.9%	0.61%	0.77%	Poor	2211	515	33	140	8	8	2.6	--	--
	Blnd2 (27%)	40.2%	0.62%	0.77%	Poor	3101	720	38	108	8	8	2.5	--	--
	MS5 (29%)	40.8%	0.60%	0.77%	Poor	3923	754	48	64	12	10	2.8	5067	6494
	MS7 (28%)	41.7%	0.58%	0.77%	Poor	3777	1589	80	76	10	12	3.0	--	--
22%	NS1 (35%)	38.6%	0.51%	0.76%	Poor	--	--	--	121	12	12	3.0	5151	6945
	NS2 (35%)	38.5%	0.51%	0.76%	Poor	2638	531	26	102	8	10	3.2	4993	6375
	MS1 (38%)	39.7%	0.47%	0.76%	Poor	2527	470	30	108	12	10	2.6	5141	6287
	Blnd1 (36%)	40.1%	0.49%	0.76%	Poor	2900	578	31	102	11	9	3.0	--	--
	Blnd2 (35%)	40.4%	0.50%	0.76%	Poor	4088	790	41	102	13	11	3.0	--	--
	MS5 (36%)	41.3%	0.48%	0.76%	Poor	4647	861	51	57	13	12	3.0	4831	6482

APPENDIX B

Chapter III

B1. Measurements of the shape properties of the sands

Table B 1. Standard Gradation of ASTM C1257-Method A

Individual sieve size	Mass (g)
No. 8 (2.36 mm) to No.16 (1.18 mm)	44
No. 16 (1.18 mm) to No.30 (600 μm)	57
No.30 (600 μm) to No.50 (300 μm)	72
No.50 (300 μm) to No.100 (150 μm)	17
Total	**190**

Table B 2. The Uncompacted Voids Content of the Sand Sources

Sand Source	NS1	MS2	MS3	MS7
Uncompacted void content	38.6%	43.9%	44.1%	49.0%
SD	0.09%	0.32%	0.19%	0.04%

B2. Evaluation of the workability performance of the concrete mixtures

Table B 3. Overall Workability Performance of the Mixtures with Different Paste Volumes

Fine sand	Blended sieved sands	Combined uncompacted voids content	Combined No. 200	Combined Fines	Overall workability performance	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (mm)	Float Test		Visual Observation	Compressive strength (Psi)	
										Hole	Texture		7-day	28-day
Mixtures with a paste volume of 26.2%														
32%	Original NS	38.6%	3.25%	0.80%	Moderate	--	--	--	127	8	7	1.0	5172	6238
30%	MS2 (13%)	39.6%	2.65%	087%	Moderate	--	--	--	108	7	5	1.4	5585	7074
	MS3 (14%)	39.7%	3.24%	0.90%	Moderate	--	--	--	108	10	9	1.4	5410	6723
	MS7 (15%)	40.3%	2.84%	0.87%	Moderate	--	--	--	121	7	6	1.4	5364	6900
27%	MS2 (37%)	40.4%	1.97%	1.04%	Unusable	--	--	--	89	16	11	1.4	4926	6080
	MS3 (38%)	40.5%	3.22%	1.15%	Unusable	--	--	--	89	15	12	2.0	4991	6320
	MS7 (30%)	41.7%	2.53%	0.95%	Unusable	--	--	--	76	15	15	2.4	5288	6687
Mixtures with a paste volume of 28.4%														
30.6%	Original NS	38.6%	3.25%	0.80%	Good	1304	384	25	152	4	3	1.0	4872	6296
27%	MS2 (29%)	40.4%	2.18%	0.97%	Moderate	2169	564	19	152	7	6	2.0	5423	6994
	MS3 (29%)	40.5%	3.23%	1.04%	Moderate	1970	649	20	146	8	6	2.0	5501	6762
	MS7 (30%)	41.7%	2.53%	0.95%	Moderate	1791	369	28	159	8	7	2.0	5783	7440
25%	MS2 (40%)	40.8%	1.91%	1.07%	Poor	2262	769	25	146	8	7	2.4	4953	6397
	MS3 (41%)	40.9%	3.22%	1.19%	Poor	2714	816	23	140	8	9	2.6	5323	6660
	MS7 (42%)	42.5%	2.33%	1.03%	Poor	2500	683	27	108	12	10	2.4	5666	6931
23%	MS2 (50%)	41.2%	1.74%	1.16%	Unusable	2295	746	32	133	10	9	3.0	4716	6091
	MS3 (51%)	41.3%	3.21%	1.35%	Unusable	3211	920	30	127	9	10	2.8	5137	5828
	MS7 (51%)	43.2%	2.2%	1.09%	Unusable	4522	840	45	108	15	11	2.8	5400	6597

Table B 3 (Continued)

Fine sand	Blended sieved sands	Combined uncompacted voids content	Combined No. 200	Combined Fines	Overall workability performance	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa/sec)	Slump (mm)	Float Test		Visual Observation	Compressive strength (Psi)	
										Hole	Texture		7-day	28-day
Mixtures with a paste volume of 30.6%														
30%	Original NS	38.6%	3.25%	0.80%	Excellent	--	--	--	203	2	2	1.0	4960	6150
26%	MS2 (36%)	40.4%	1.03%	2.00%	Good	1652	413	32	165	4	5	1.0	5700	7440
	MS3 (39%)	40.9%	1.16%	3.22%	Good	1802	376	30	178	5	4	1.0	5220	6230
	MS7 (33%)	41.9%	2.48%	0.97%	Good	1224	354	21	197	5	4	1.0	5200	6200
25%	MS2 (48%)	41.1%	1.14%	1.77%	Good	--	--	--	133	8	4	1.0	5080	6520
	MS3 (49%)	41.4%	1.32%	3.21%	Moderate	1843	456	38	159	6	5	1.0	5180	6000
	MS7 (41%)	42.7%	2.35%	1.02%	Moderate	1155	404	24	190	6	4	1.0	5070	6450
24%	MS2 (59%)	41.6%	1.26%	1.60%	Moderate	--	--	--	121	8	5	1.8	4800	6500
	MS3 (61%)	42.0%	1.56%	3.20%	Moderate	2085	611	33	152	6	6	1.6	4710	6620
	MS7 (50%)	43.5%	2.23%	1.08%	Moderate	1802	376	30	178	5	4	1.8	4890	6500
22%	MS2 (77%)	42.6%	1.53%	1.39%	Poor	--	--	--	108	10	7	2.8	4800	6660
	MS3 (80%)	43.0%	2.20%	3.19%	Poor	2168	792	31.5	114	13	12	3.0	4690	6330
	MS7 (63%)	44.9%	2.05%	1.19%	Poor	--	--	--	102	2	2	2.8	4910	6600
Mixtures with a paste volume of 32.8%														
30%		38.6%			Excellent	--	--	--	216	2	1	1.0	4620	6100
21%	MS2 (75%)	42.5%	1.41%	1.50%	Good	--	--	--	133	6	4	1.0	5280	6620
	MS3 (80%)	43.0%	3.19%	2.20%	Good	--	--	--	140	6	4	1.0	5020	6150
	MS7 (78%)	46.5%	1.89%	1.34%	Good	--	--	--	140	5	5	1.0	4920	7080
19%	MS2 (91%)	43.5%	1.26%	1.84%	Moderate	--	--	--	121	7	5	2.2	5230	6800
	MS3 (92%)	43.7%	3.18%	2.96%	Moderate	--	--	--	108	7	6	2.4	4790	6540
	MS7 (87%)	47.5%	1.81%	1.45%	Moderate	--	--	--	133	8	6	2.6	5260	6950
18%	MS2 (100%)	44.0%	1.19%	2.10%	Poor	--	--	--	114	8	7	3.0	4880	6300
	MS3 (100%)	44.2%	3.17%	3.85%	Poor	--	--	--	102	8	6	3.0	4690	6060
	MS7 (100%)	49.0%	1.70%	1.63%	Poor	--	--	--	121	10	6	3.0	5070	6840

Cells containing “--“indicate that the parameter was not measured due to device unavailability at the time of testing. Note: NS: natural sand and MS: manufactu

B3. Compressive strength

B3.1 Methods for curing and concrete compressive strength

Standard cylinder molds were used for the compressive strength test with a size of 4 × 8 in. (100 mm × 200 mm). Molds were filled and consolidated as per ASTM C31 [17]. The samples were stored in a temperature-controlled and moisture-controlled room for curing purposes, as specified in the ASTM C31. Concrete compressive strength test was conducted at 7 and 28 days on hardened concrete in accordance with ASTM C39 [18].

B3.2 Compressive strength results and discussion

Recall that the tested mixtures had the same mixtures design, however, different manufactured sand sources were used to replace the natural sand incrementally. Also, different paste contents were used in these mixtures. Table A2 shows the average compressive strength data of concrete mixtures blended with different sources of manufactured sand and different paste contents at 7 and 28 days. Fig. B1 through Fig. B4 plots the compressive strength data at 7-day while Fig. B5 through Fig. B8 plot the compressive strength at 28-days. Each line contains dots, which represent a fine sand content and compressive strength of a mixture containing a manufactured sand source. The color of the dots on each line represents a workability performance.

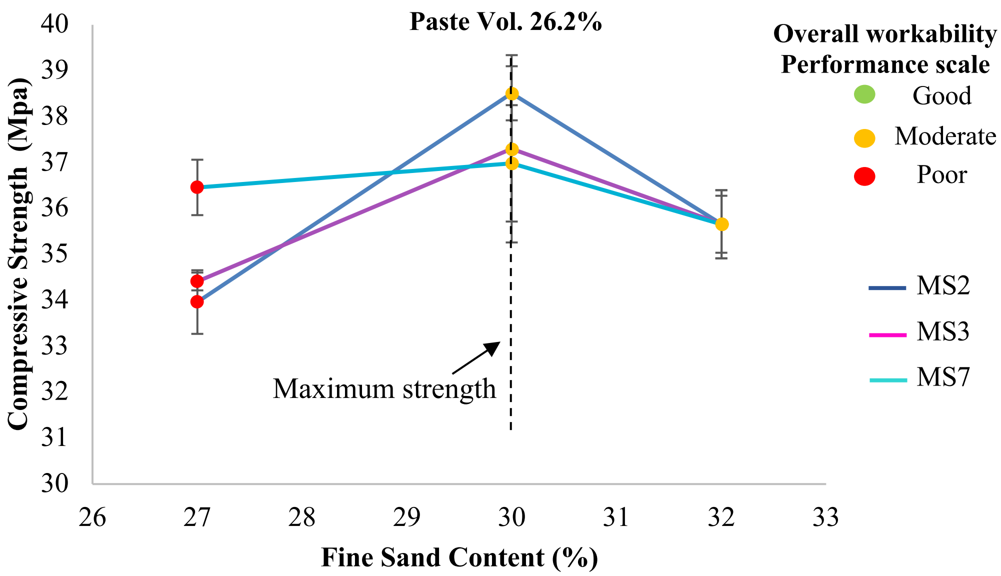


Figure B 1 plots the 7-day of the compressive strength of the concrete mixtures with different manufactured sand sources at 26.2% paste volume.

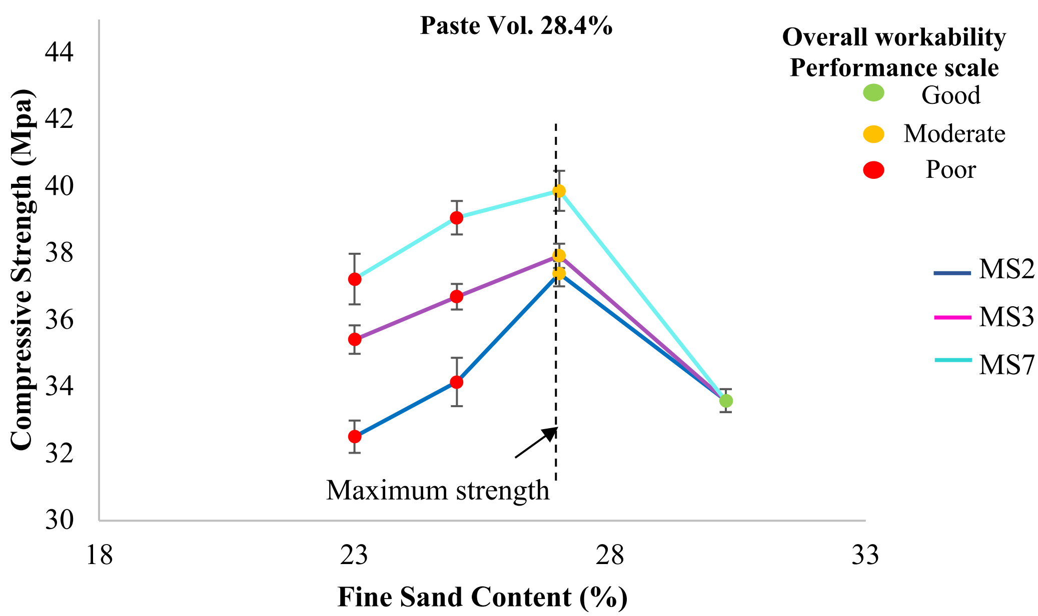


Figure B 2 plots the 7-day of the compressive strength of the concrete mixtures with different manufactured sand sources at 28.4% paste volume.

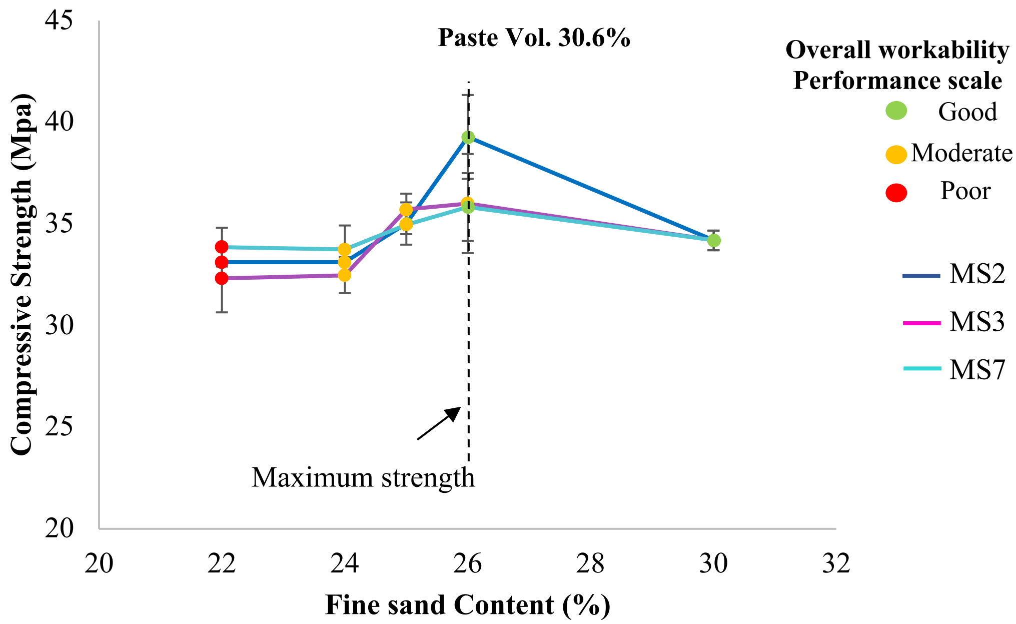


Figure B 3 plots the 7-day of the compressive strength of the concrete mixtures with different manufactured sand sources at 30.6% paste volume.

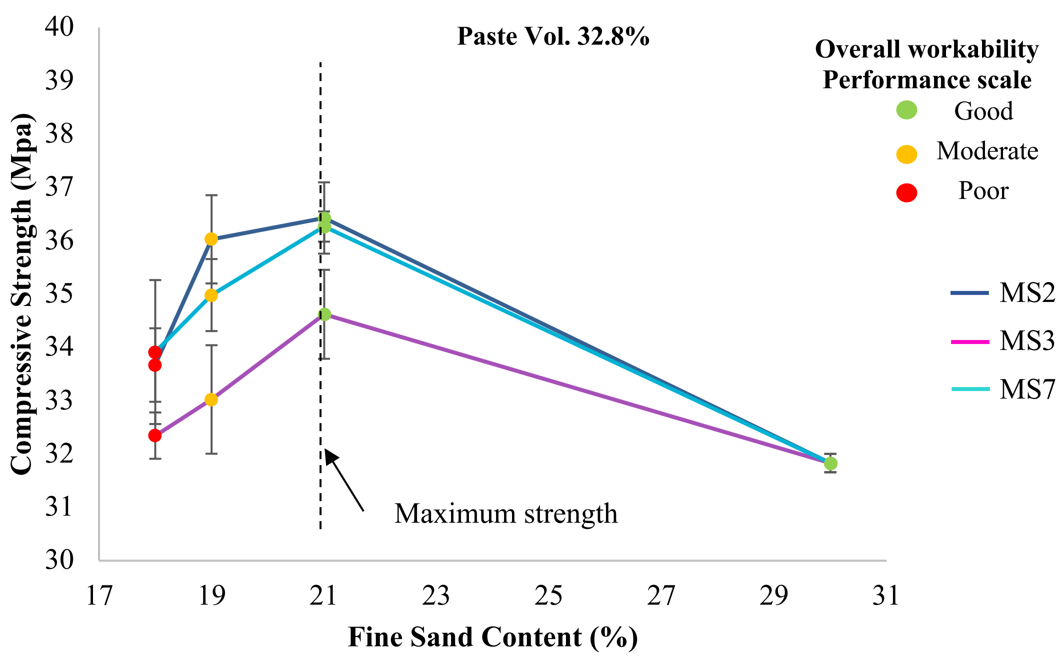


Figure B 4 plots the 7-day of the compressive strength of the concrete mixtures with different manufactured sand sources at 32.8% paste volume.

For the short-term compressive strength (7-day), there was a drop in the compressive strength of the concrete mixtures containing manufactured sand right after exceeding the minimum fine sand content limit for the mixtures with a paste volume of 26.2% and 28.4%, respectively. This drop-in strength can be attributed to the change in the workability performance as the mixtures showed a loss in strength when the workability was poor. However, a different trend was observed for mixtures with a paste volume of 30.6% and 32.8%, shown in Fig. B3 and Fig. B4, respectively where the drop where those mixtures gained strength as the manufactured sand volume increased, then the compressive strength dropped before the performance of those mixtures changed to poor. This could be attributed to using higher paste volume, and the paste is weaker than the aggregates.

For the long-term strength, a similar trend was noticed compared to the short-term strength where there was a drop in the strength due to reaching the poor performance. This is valid for the mixtures with the paste volumes of 26.2%, 28.4%, and 32.2%. Also, no sharp peak was observed in the 28-days compressive strength, especially for the mixtures with the paste volumes of 30.6% and 32.8%. This means that improvement in strength made by the interlocking of the manufactured may not be as important at higher paste volumes and later ages.

The difference in the compressive strength behavior between the short-term and the long-term could be because the paste is weaker at 7 days and so the strength of the concrete is dominated by the aggregate. However, in later ages, the concrete strength is a combination of the strength of the paste and the aggregate.

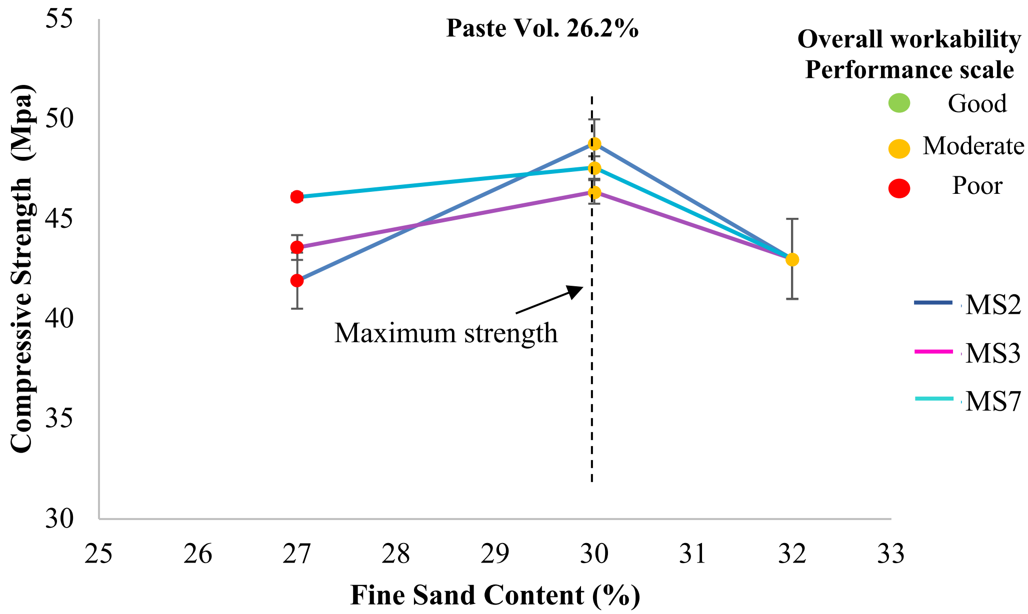


Figure B 5 plots the 28 -day of the compressive strength of the concrete mixtures with different manufactured sand sources at a paste volume of 26.2%.

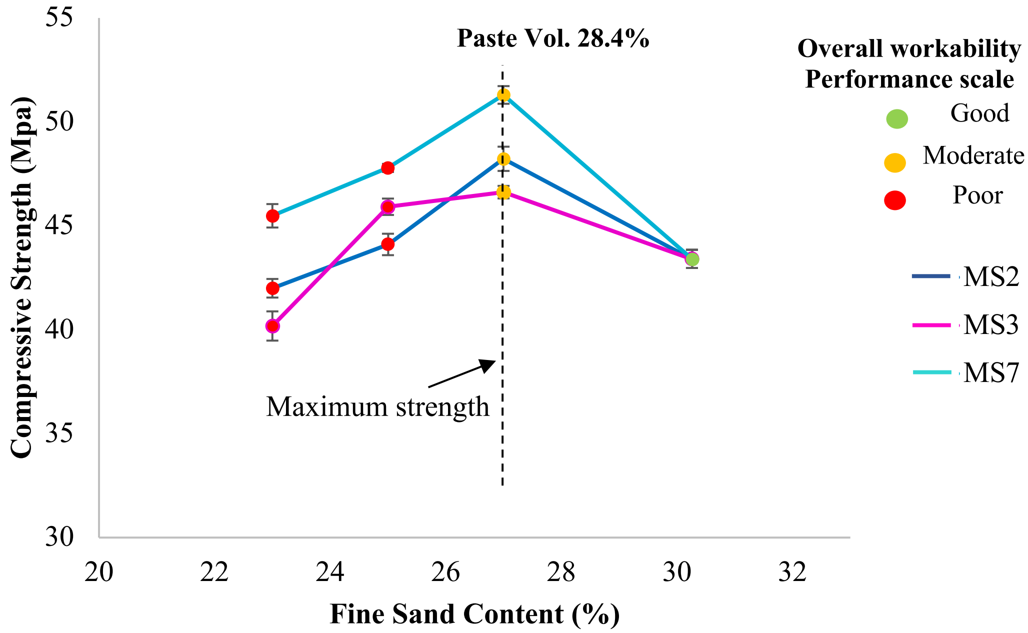


Figure B 6 plots the 28 -day of the compressive strength of the concrete mixtures with different manufactured sand sources at a paste volume of 28.4%.

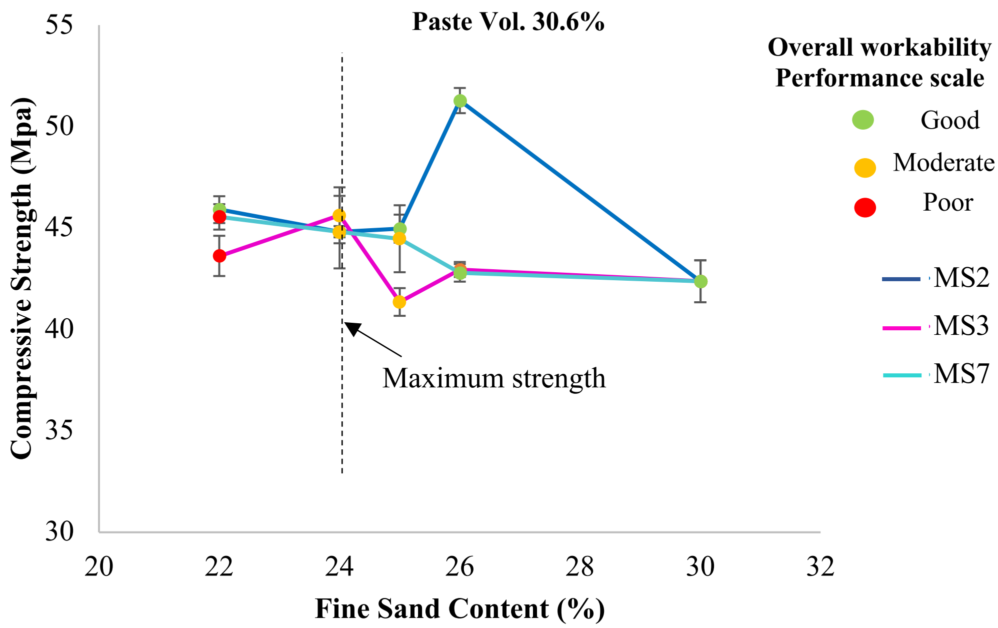


Figure B 7 plots the 28 -day of the compressive strength of the concrete mixtures with different manufactured sand sources at a paste volume of 30.6%.

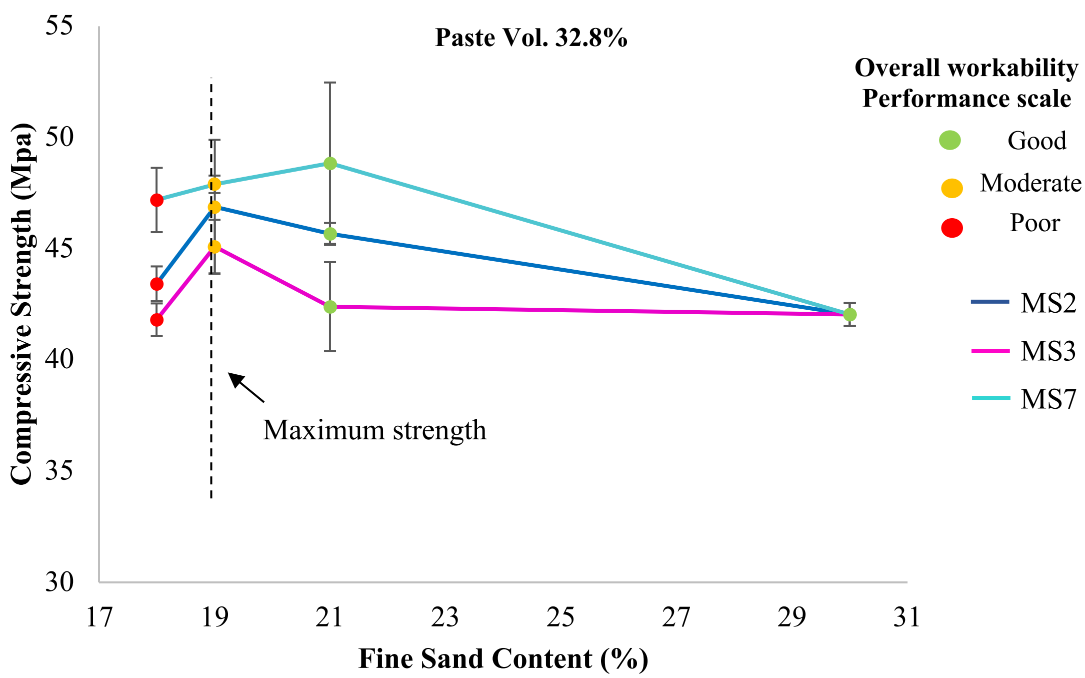


Figure B 8 plots the 28-day of the compressive strength of the concrete mixtures with different manufactured sand sources at a paste volume of 32.8%.

Fig. B9 shows a linear relationship with R^2>0.93 between the paste volume (total cementitious materials sacks) and the fine sand at the maximum compressive strength in which as the paste volume increased in a mixture with blended sand, the fine sand content to produce the maximum compressive strength decreased. This shows that the paste is replacing the required amount of fine sand; thus, increasing the manufactured sand volume in the mixture. The manufactured sand would provide angular particles that improve the interlock in the aggregate matrix and improve the compressive strength of the concrete.

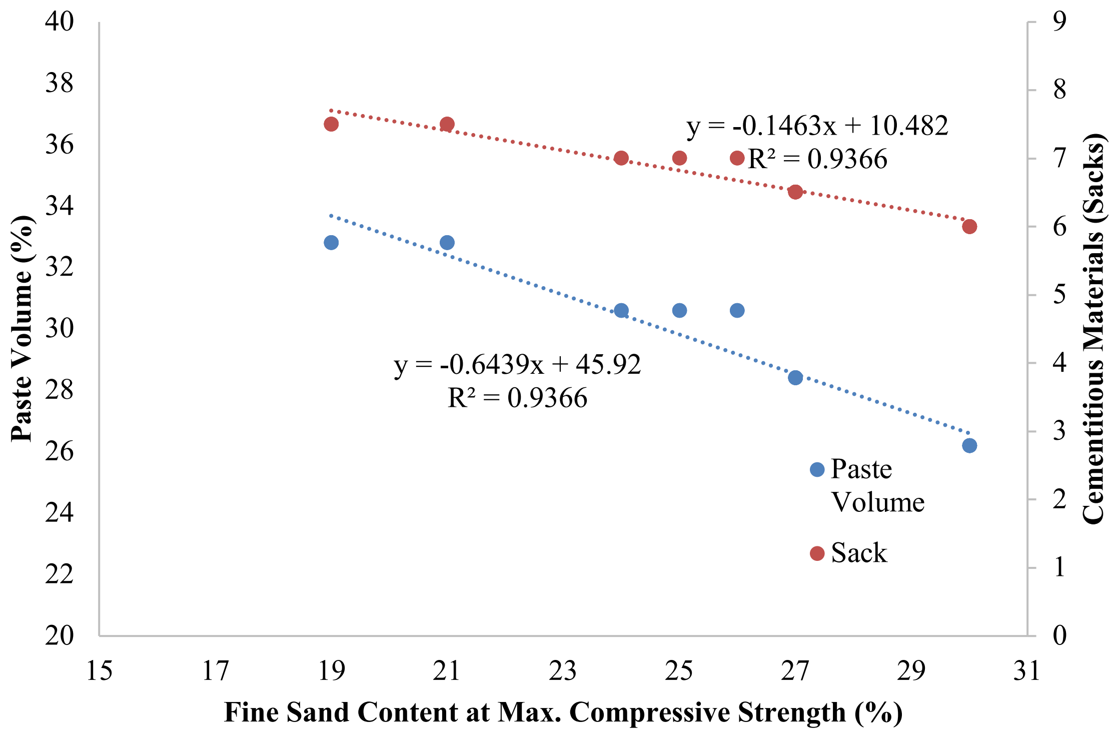


Figure B 9 plots the fine sand contents at the maximum compressive strength versus each paste volume and cementitious material content for mixtures with blended sand.

APPENDIX C

Chapter IV

C1. Sensors assembly

Since the sensors would be damaged when directly contacting the concrete, a buffer chamber, filled with incompressible oil, was used with a flexible membrane at one end, and a sensor at the other end. When the concrete pressure in the pipe increased, it would push the membrane, which would pressurize the oil in the chamber, then, the sensor would read these changes in the pressure. The sensor assembly is shown in Fig. 6. These sensors can read pressure in the pipeline every 0.02 seconds. The sensor was attached to the pipe by drilling a hole with a diameter of 1.125 in. and a nut was welded to the outside of the pipe so that the chamber can be screwed into the nut until the membrane was adjacent to the inner pipe wall. Each sensor was positioned at an angle of 30° from the vertically downward direction to prevent concrete from mounting on top of the flexible membrane, which helps maintain the accuracy and the sensitivity of the sensors.

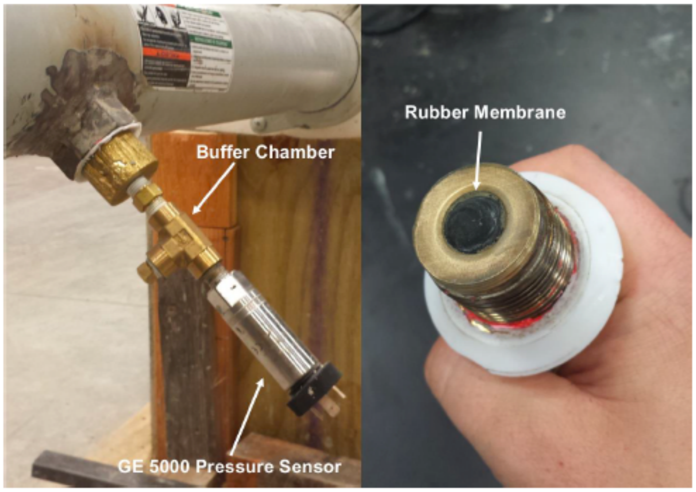


Figure C 1 shows an overview of a pressure sensor [21].

C2. Sensors calibration

To ensure the performance and repeatability of the sensors, each sensor was calibrated by attaching it to a pipe filled with water where the pressure inside the pipe can be systematically increased from 0 psi to 110 psi. By plotting the voltage reading from the sensors and the pressures inside the pipe, a calibration curve was obtained. An example of typical calibration results can be seen in Fig. 7. It is important to know that the y-intercept value changes slightly over time between 0 to 20 psi; however, the slope of the line remains the same, which could be attributed to the wear and the relaxation of the rubber membrane attached to the sensor [9, 21]. To account for that change, the pressure in the pipeline was recorded prior to pumping the concrete, empty pipeline, to measure the zero pressure. Then, the increase in the pressure was added to the initial value [21].

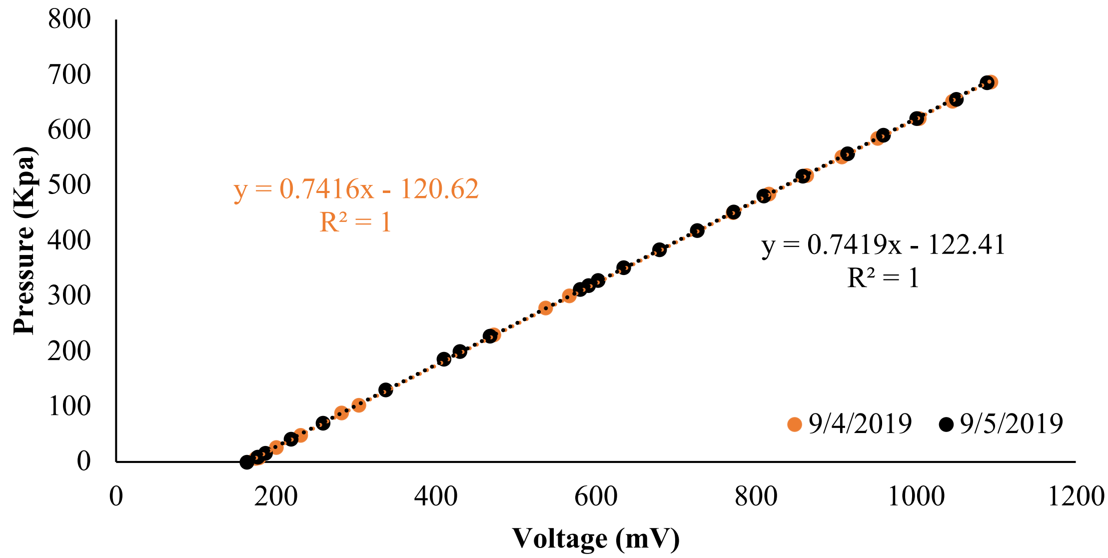


Figure C 2 illustrates a sensor calibration using the best fit line between the voltage and the pressure obtained from the pressure chamber filled with water.

C3. Concrete mixtures detailed results

Table C 1 Workability Evaluations for The Investigated Mixtures

Source	Fine sand content	Combined uncompacted voids content	No. 200 materials (%)	Fines (%)	Time (min)	Static (pa)	Dynamic (pa)	Plastic Viscosity (pa/sec)	Slump (mm)	Overall workability performance
NS1	34%	38.6%	0.80	3.25	0	1183	472	18	216	Good
					15	1851	772	12	165	Moderate
					30	3267	976	24	114	Poor
Blended sand: NS1 + MS1	29%	39.3%	0.44	1.62	0	1557	646	20	152	Good
					15	2128	847	18	140	Moderate
					30	3975	1000	35	95	Poor
	25%	39.7%	0.33	1.17	0	1575	538	25	165	Moderate
					15	2009	663	22	146	Moderate
					30	3040	1039	24	89	Poor
	23%	39.9%	0.30	1.07	0	2100	653	34	114	Moderate
					15	2674	997	21	95	Poor
					30	4425	1112	32	64	Poor
Blended sand: NS1 + MS4	29%	40.0%	0.88	3.05	0	1691	752	21	140	Moderate
					15	2026	887	22	140	Moderate
					30	3002	1163	27	89	Poor
	27%	41.2%	0.95	2.93	0	2477	1073	25	121	Moderate
					15	2668	1210	19	102	Poor
					30	3462	1436	35	64	Unusable
	25%	41.9%	1.00	2.85	0	4412	1640	40	64	Unusable
					15	--	--	--	--	Too stiff
					30	--	--	--	--	Too stiff
Blended sand: NS1 + MS7	29%	41.4%	0.96	2.46	0	1613	481	23	165	Moderate
					15	1771	735	16	146	Moderate
					30	3323	1000	42	76	Poor
	27%	42.7%	1.05	2.24	0	1667	533	26	152	Moderate
					15	2999	804	21	140	Poor
					30	4055	1244	47	64	Unusable
	25%	43.8%	1.14	2.08	0	4538	925	39	64	Unusable
					15	1183	472	18	216	Too stiff
					30	1851	772	12	165	Too stiff

Table C 2 Average Secondary Curve Pressures of Each Mixture Over Time

Source	Fine sand content	Combined uncompacted voids content	Time (min)	Sensor 1 (kpa)	SD (kpa)	Sensor 2 (kps)	SD (kpa)	Sensor 3 (kpa)	SD (kpa)	Sensor 4 (kpa)	SD (kpa))
NS1	34%	38.6%	0	336	--	307	--	271	--	176	--
			15	376	--	339	--	305	--	199	--
			30	496	--	446	--	412	--	285	--
Blended sand: NS1 + MS1	29%	39.3%	0	467	5	362	6	209	8	176	5
			15	478	3	376	4	270	10	197	10
			30	553	1	432	2	328	2	295	8
	25%	39.7%	0	469	3	371	5	304	3	163	3
			15	503	23	398	16	326	14	196	8
			30	552	48	422	41	341	33	276	28
	23%	39.9%	0	552	4	414	6	310	8	174	6
			15	572	5	442	3	331	3	205	6
			30	679	9	510	10	401	6	317	11
Blended sand: NS1 + MS4	29%	40.0%	0	550	8	324	10	254	6	124	8
			15	572	5	353	3	272	2	139	3
			30	679	5	470	5	316	3	165	3
	27%	41.2%	0	500	4	356	6	293	4	221	3
			15	494	5	371	4	297	4	228	3
			30	625	3	462	3	361	2	248	3
	25%	41.9%	0	687	59	490	35	396	36	262	26
			15	--	--	--	--	--	--	--	--
			30	--	--	--	--	--	--	--	--
Blended sand: NS1 + MS7	29%	41.4%	0	476	7	383	5	284	2	error	2
			15	500	34	414	35	321	32	error	21
			30	609	2	510	1	376	1	error	3
	27%	42.7%	0	490	4	355	6	316	3	142	3
			15	522	5	393	5	346	4	180	4
			30	657	3	497	3	440	2	256	3
	25%	43.8%	0	695	15	523	16	433	14	163	12
			15	--	--	--	--	--	--	--	--
			30	--	--	--	--	--	--	--	--

C4. Concrete mixtures detailed results and figures

C4.1Workability performance versus pump pressure

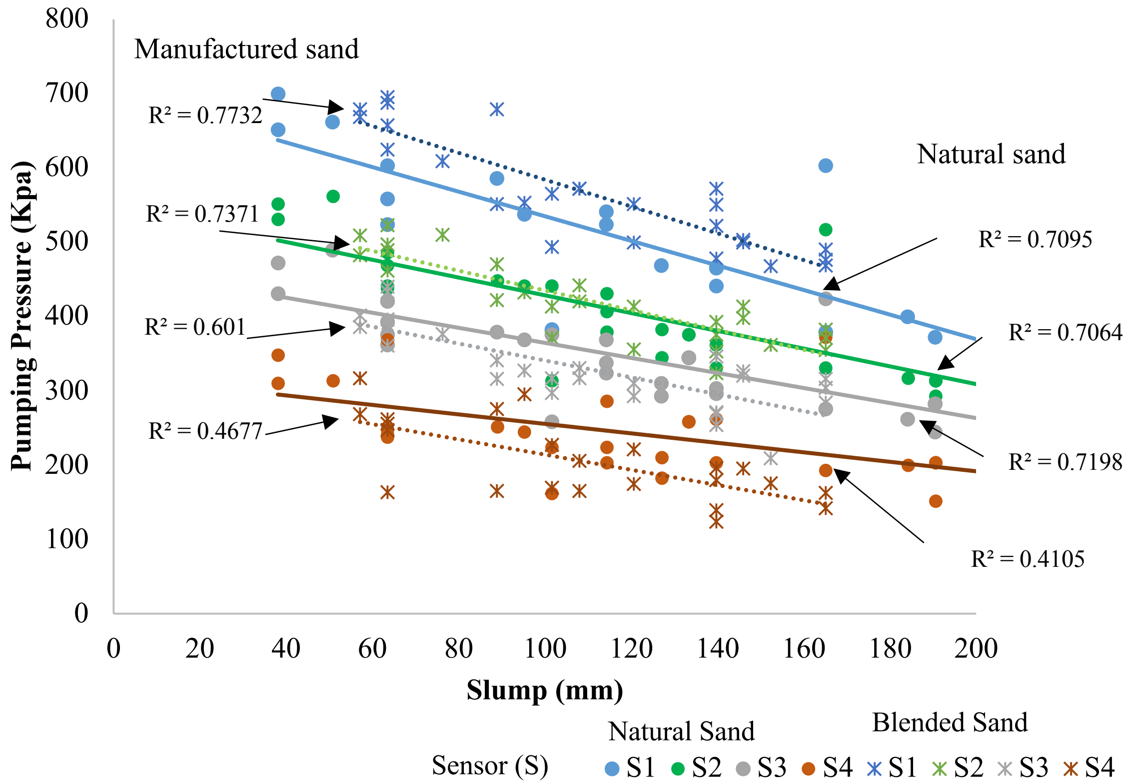


Figure C 3 shows a comparison between mixtures with natural sand and mixtures with blended sand. Note S: sensor, NS: natural sand, and MS: manufactured sand

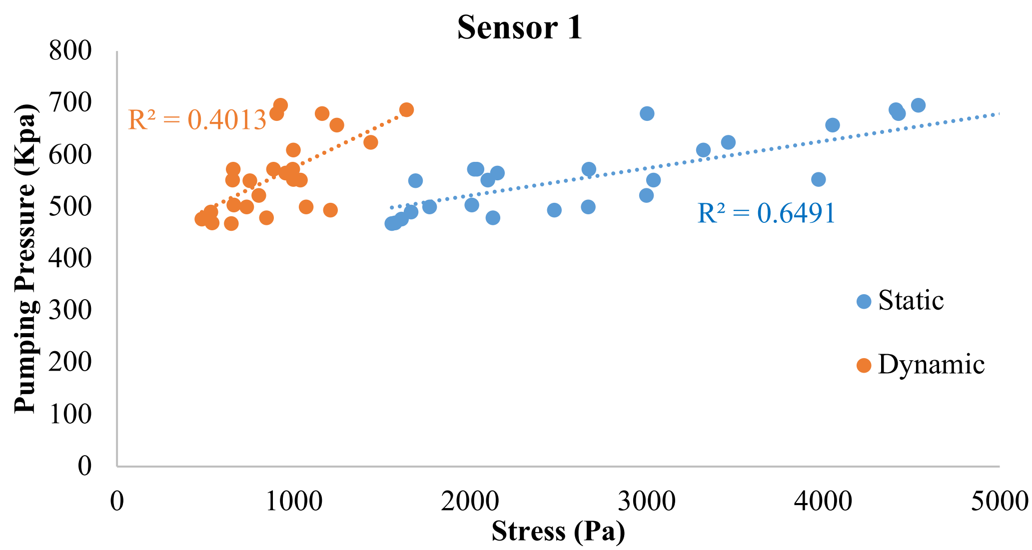


Figure C 4 plots sensor 1 pressures at 1500 rpm versus the rheometer yield stresses (static and dynamic).

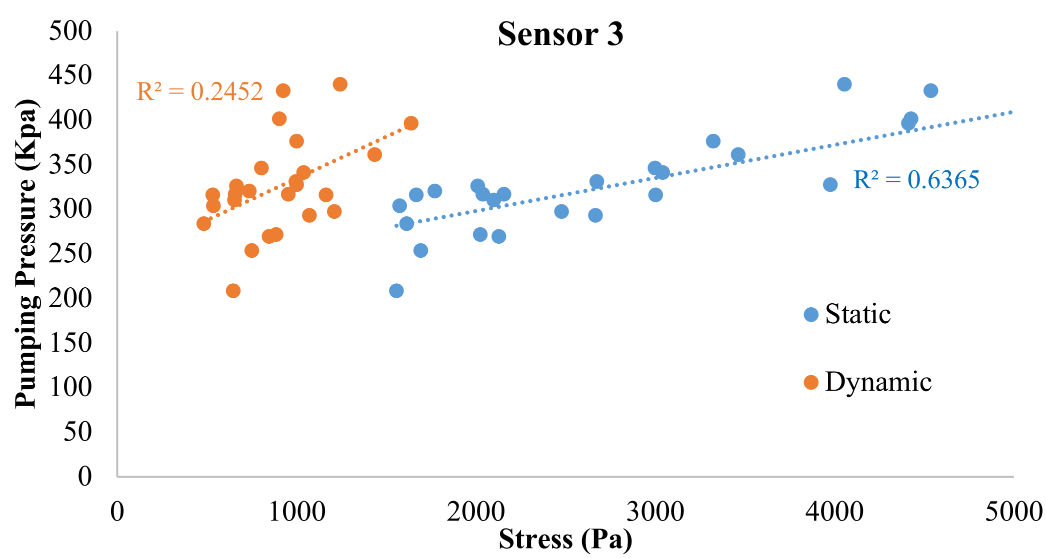


Figure C 5 plots sensor 3 pressures at 1500 rpm versus the rheometer yield stresses (static and dynamic).

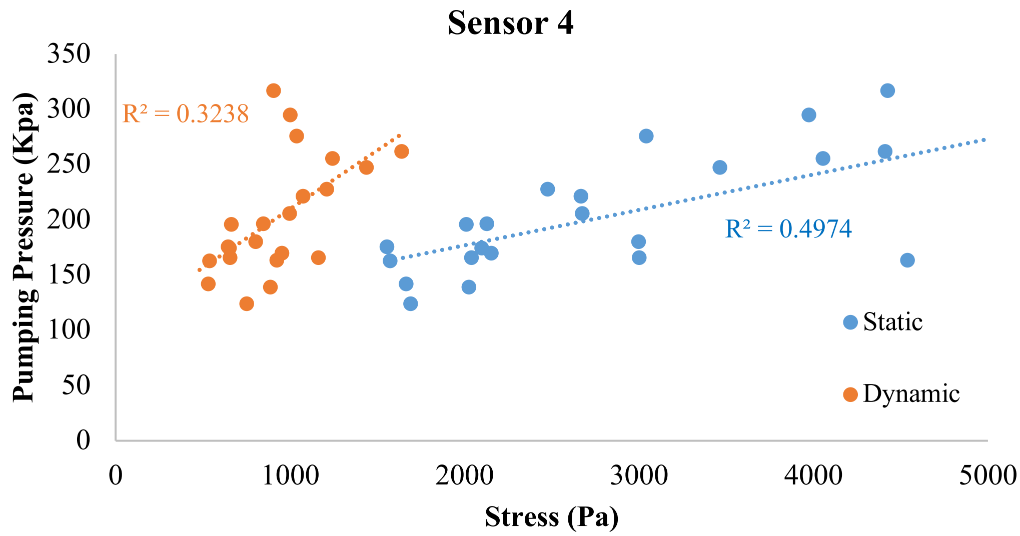


Figure C 6 plots sensor 4 pressures at 1500 rpm versus the rheometer yield stresses (static and dynamic).

C4.2 Workability performance versus fine sand content

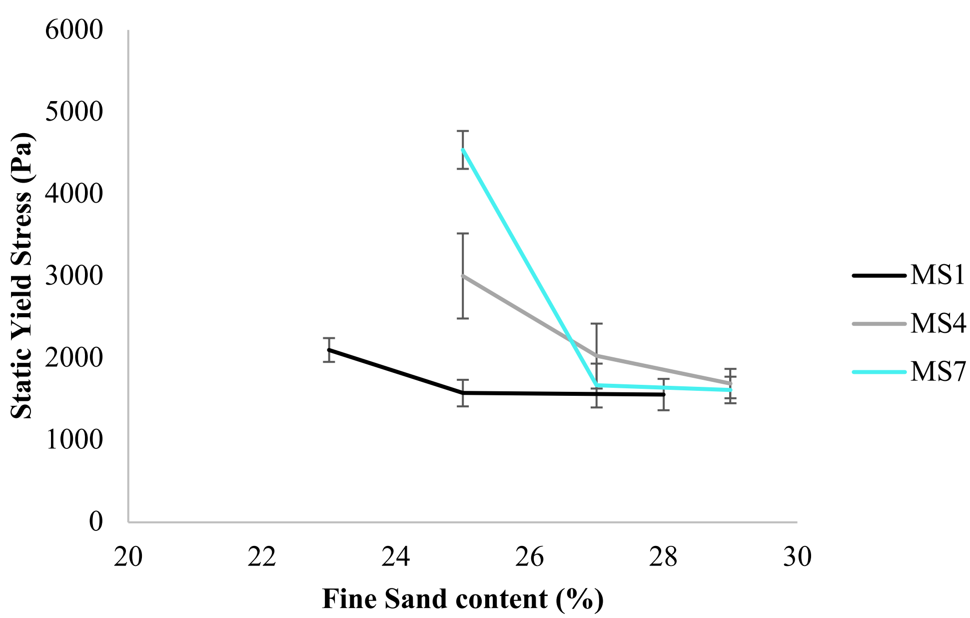


Figure C 7 shows the static yield stress, at 0 min. testing interval, versus fine sand contents.

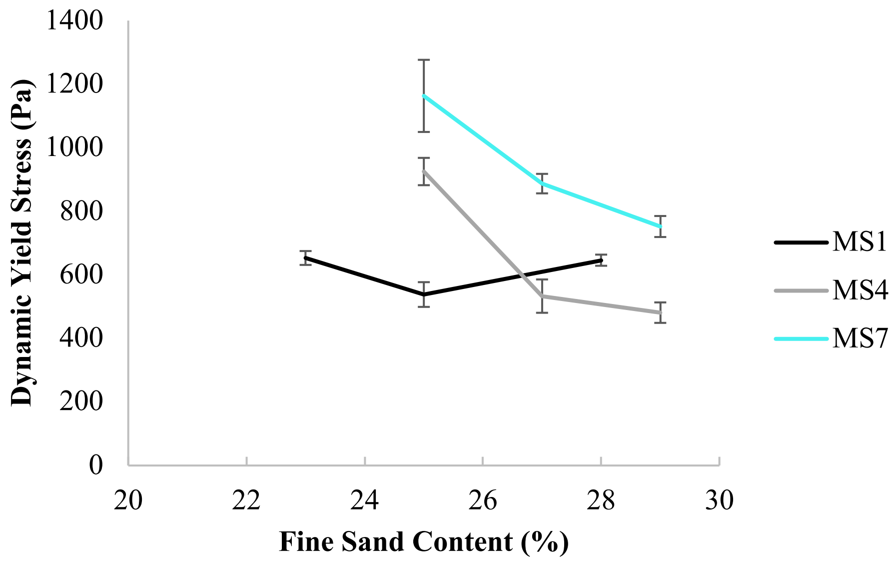


Figure C 8 shows the dynamic yield stress, at 0 min. testing interval, versus fine sand contents.

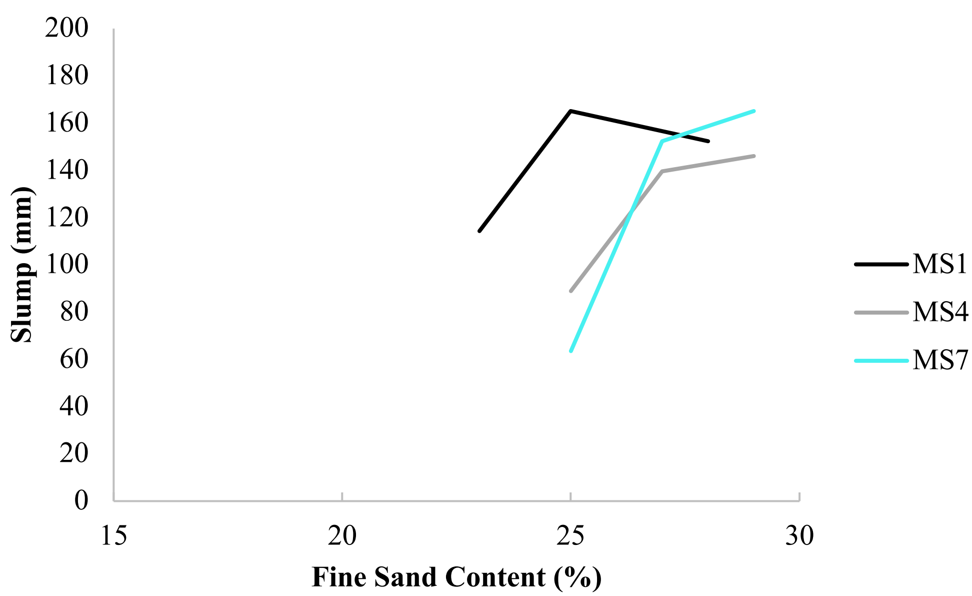


Figure C 9 shows the slump data, at 0 min. testing interval, versus fine sand contents.

VITA

Riyadh Turki M Alturki

Candidate for the Degree of

Doctor of Philosophy

Dissertation: PROPORTIONING MANUFACTURED SAND IN FLOWABLE CONCRETE

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2020.

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in 2016.

Completed the requirements for the Bachelor of Science in Civil Engineering at King Saud University, Riyadh, Saudi Arabia in 2012.

Professional Memberships:

American Concrete Institute (ACI)