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Investigating the effects of aggregate gradations on the compressive strength and the cost of concrete using two proportioning methods

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ABSTRACT

Optimizing aggregate gradation in concrete mixtures has an impact on concrete properties such as strength, durability and sustainability. Many aggregate proportioning methods have been proposed to solve aggregate gradation issues. The Tarantula Curve is a recently developed aggregate proportioning technique that can evaluate aggregate gradations and can give insights of the quality of the gradations. Since the Tarantula Curve have been having great success in the United States in producing concrete mixtures with outstanding performances and lower cost, this work aims to validate the gradation boundaries of the Tarantula Curve using local aggregates in Saudi Arabia by measuring the compressive strength and the workability. This work also provides a comparison between the Tarantula Curve method to the ACI 211. The results showed a reduction in the compressive strength and poor workability when the 20% limit is exceeded for the coarse aggregate retained on a single sieve. Similarly, as the limits of sieve sizes 150 μm and 75 μm were exceeded, the compressive strength decreased, and poor workability performance was observed in the mixtures. Harsher mixtures were produced as the 2.36 mm sieve limit was exceeded. It was found that the Tarantula Curve produced mixtures with a 35% higher in compressive strength and 6% lower in cost as opposed to the ACI 211 mixtures. These data and tests provide recommendations and framework for further comparative testing in the durability testing in the future

1 Introduction

Concrete is a construction material used worldwide extensively due to its strength, durability, and availability of its raw materials. The core compositions of concrete are cement, aggregates, water and plus mineral admixtures are added to enhance certain properties such as strength and workability. The consumption of concrete in construction industries has increased drastically over the last decades. Currently, concrete is consumed at a rate of 4.4 billion tons annually. Based on the Chatham House Report, this rate is expected to elevate to above 18 billion tons by 2050 because of large urbanization around the world [1].

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Cement in concrete is the most expensive ingredient due to the intense energy and raw materials required to produce it. In addition, 8% of planet-warming carbon dioxide emission comes from cement production [2]. Good quality aggregates sources are becoming scarce because of the large demand in the concrete construction industry [1].

Due to the global warming and deficiency of good quality local raw materials for concrete, the sustainability of concrete become a subject of interest. The sustainability of concrete can be improved by making it more environmentally friendly. To do that, researchers have been trying to develop approaches to modify the concrete design to produce concrete that is more sustainable. Concrete producers have been looking towards methods to design concrete that is economical [3-5].

It is globally common practice to use the ACI-211 mix design method to design concrete mixtures. It uses the nominal maximum coarse aggregate size as an indicator for the workability of a mixture in which the higher the maximum aggregate size, the better the workability [6, 7]. However, this is not always the case. Cook et al.(2016) showed that using larger maximum aggregate size reduced the workability in several situations [8]. Also, the ACI-211 concrete design method uses the dry-rodded unit weight in proportioning coarse aggregates via knowing the voids content. It was proved that voids content did not have major effect on the workability of a mixture and more emphasis should be put on the individual gradation for each sieve size [8, 9]. Lastly, ACI-211 method uses the Fineness Modulus (FM) to describe a distribution of aggregate particles in a gradation. This FM is used to describe any gradation source, either coarse, intermediate, or fine aggregates, as well as combined gradations. It worked well in the past when good quality aggregates were available. However, with the complexity and variation of aggregate gradations and the lack of good quality aggregate sources, the FM lacked details to show problems with combined gradations. In addition, the ACI 211 mixtures tend to have more paste content as opposed to other mix design methods and applies only to aggregates that meet the ASTM C 33 [8, 9]. Thus, alternative approaches were developed over the last decades to design concrete mixtures where the effect of aggregates gradations was considered.

1.1. Aggregate gradation

Aggregates in concrete are classified into categories such as coarse, intermediate, and fine aggregates, determined by sieve analysis test [9], with specified standards, listed in ASTM C33 [10]. These standards in the ASTM C33 are broad, and they are derived based on practical experiences from aggregate and concrete producers without assuring the performance [11, 12]. In concrete mixtures, it has been commonly to use different combinations of aggregates, (coarse, intermediate, and fine aggregates), in which individually it can meet the ASTM C33 broad limits but when these aggregates are combined, a good quality aggregate gradation cannot be guaranteed. Thus, the ASTM C33 limits may not be used by themselves to provide sufficient guidance to obtain good quality aggregate gradations. Thus, researchers developed methods where they could investigate various combinations of coarse, intermediate and fine aggregates and their performances. These methods aimed to optimize the aggregate gradation to produce optimized graded concrete that has lower paste content and yet meet specifications with a good performance [8, 11-14]. Power 45, Shellstone, 8-18 chart are one of famous methods of assessing combined aggregate gradations. However, the bases of these methods have been from field experience [12-15]. The most recent method to optimize the aggregate gradation is called The Tarantula Curve developed by Cook et al. in his PhD dissertation [8]. A summary from the literature about each method is provided below.

1.1.1 Power 45 chart

It was created by Fuller in 1907 and mainly used in the asphalt industry. In this method the combined gradation of different aggregate sizes is plotted with the sieve sizes raised to the 0.45 power on the cumulative percent passing chart. The chart has a maximum density line represented by a straight line, which starts from the origin to the nominal maximum aggregate size (NM). Combined gradations that are close to the straight line will have maximum density, less voids contents [12, 13]. Research was conducted to investigate the Power 45 method. It was concluded that using the power 45 method to proportion combined aggregate gradations that fit with the best-fit line does not guarantee the performance of mixtures and sometimes two combined aggregate gradations would have different performances even though the gradation is very similar [8]. In addition, the boundary limits for fine aggregates on the power45 chart are short spaced, which is not practical [8]. Finally, it was found that using the power 45 chart, or the minimum voids content is not recommended for proportioning concrete mixtures for slip-formed pavement [8].

1.1.2 Coarseness factor chart

It is another technique developed by James Shilstone to proportion aggregates through a combined gradation. The method relies on the workability factor (WF) and the coarseness factor (CF). A point is plotted on the Shellstone chart using these factors. The Shellstone chart is divided into different zones as shown in Fig. 1.

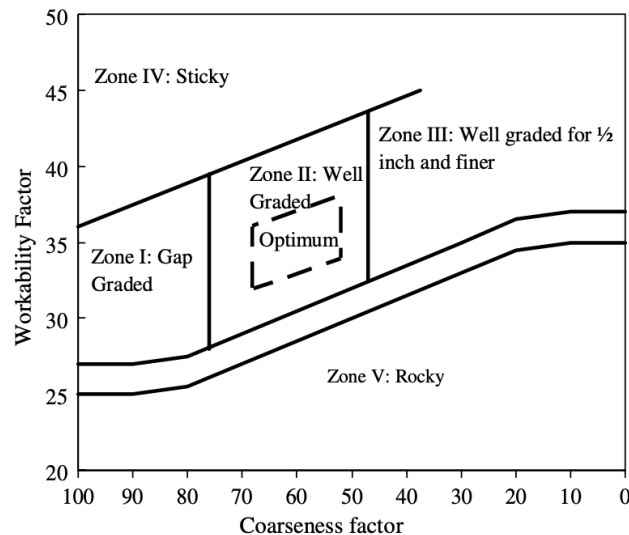


Fig. 1 - Coarseness factor chart developed by Shells one

Each zone has characteristics that differ from other zones. It is said that Zone II is preferable for concrete mixtures and some researchers had even developed sub-zones for different applications, such as the slip-formed mixtures. [11-13]. However, no sufficient research has been conducted for validating the chart. Also, it was demonstrated in a research project that a single location or zone on the chart does not predict the concrete performance and the lack of details and mechanisms in this method to address the workability of a concrete mixture [8].

1.1.3 Individual percent retained chart (IPR)

This method has the ability to determine the excess/deficient percentage amount retained on each sieve size in a combined aggregate gradation. It provides a maximum limit of 18% and a minimum limit of 8% per each sieve size from 19 mm (3/4") to 0.3 mm (#50) as shown in Fig 2.

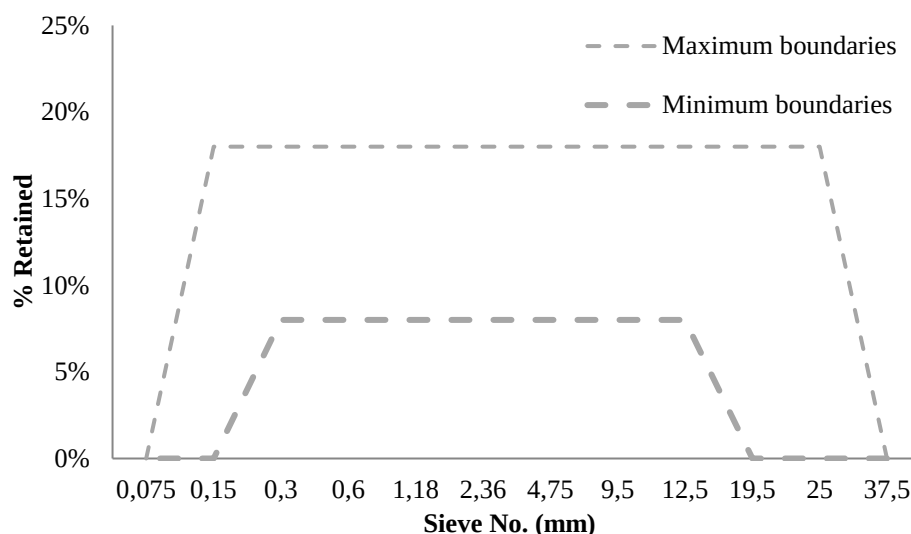


Fig. 2 - 8-18 chart for aggregate optimization.

Researchers also developed alternative limits for the same set of sieve sizes with maximum boundaries ranging from 15% to 22% and minimum boundaries ranging from 5% to 12% [15]. Even though the IPR shows useful guidance and provides limits for each sieve size, the amount of research conducted for validation of these boundaries is limited [13, 16, 17].

1.1.4 The Tarantula Curve

The Tarantula Curve is a recently developed proportioning technique that can evaluate aggregate gradations that has been showing great success in the United States in producing concrete mixtures with outstanding performances and lower cost. The Tarantula Curve is an improved IPR version where it is an advanced technique to proportion aggregates for concrete. It has shown great success in producing good quality concrete for both slip-form concrete and flowable concrete [8, 18, 19]. This method provides a thorough approach in designing a combined aggregate gradation via specific recommendation for each sieve size. Plus, the Tarantula Curve provides additional criteria for fine aggregate by dividing it into two parts the coarse sand and the fine sand contents. The coarse sand is the sum of the materials retained on the sieve sizes from 2.36 mm (No.8) to 600 μ m (No.30) in which it contributes to the cohesive properties of a concrete mixture. The fine sand is the sum of the materials retained on the sieve sizes from 600 μ m (No. 30) to 75 μ m (No. 200) in which it affects the concrete workability and stickiness [8, 18]. The Tarantula Curve is shown in Fig. 3.

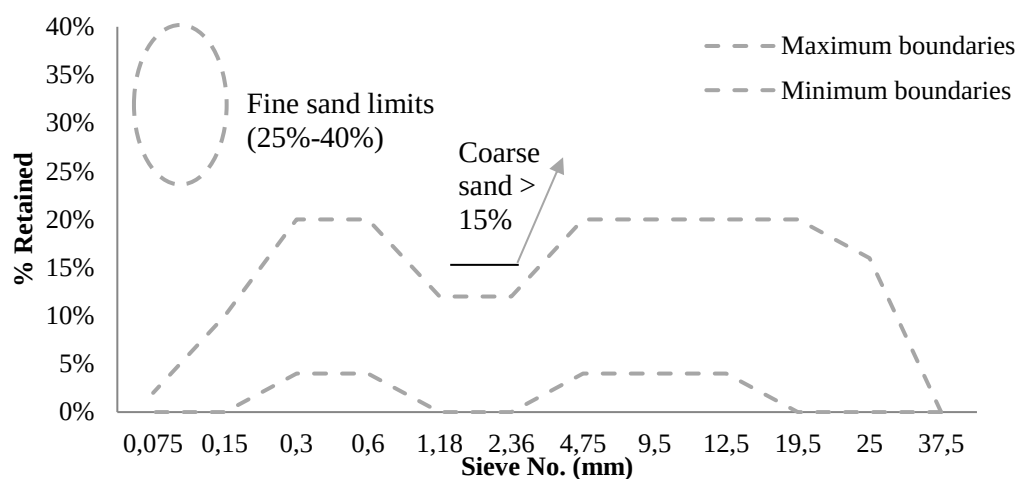


Fig. 3 - Tarantula Curve for proportioning aggregates in concrete mixtures

One of the powerful features of the Tarantula Curve technique is that it provides limits for each sieve size and can predict the issues of exceeding these assigned limits. Also, it can predict the concrete finishability issues, when exceeding the sieve sizes 2.36 mm and 1.18 mm (#8 and #16). The Tarantula Curve provides basics and simple guidelines to proportion “fine sand” and “coarse sand” in a combined gradation. All these guidelines provided in the Tarantula Curve were proved to be beneficial in construction specifications and practices as well as giving the ability of a mixture to decrease the cementitious materials demand, thus, reducing the cost of a mixture, improving concrete durability, and lowering the CO₂ emissions [8, 18, 19].

Sokhansefat (2019) investigated the Tarantula Curve boundaries by evaluating concrete mixtures with various aggregate gradations and workability and tested the aggregate packing in hardened concrete via X-ray computed tomography (XCT). It was found that for the gradations that didn’t satisfy the Tarantula Curve boundaries, with more than 20% of the coarse aggregates retained on a single sieve, the workability measurements showed segregations/ poor workability [20]. The Tarantula Curve was used to design pumpable concrete mixture and to investigate its feasibility in producing pumpable mixtures. It was concluded that being inside the limits of the Tarantula Curve along with the total fine sand limits yielded the lowest pump pressures mixtures as opposed to the mixtures that did not meet the specified limits [21].

1.2. Problem statement

Recently in Saudi Arabia, a new initiative toward the sustainability has taken place in accordance with the Saudi Arabia Vision 2030. Concrete industry in Saudi Arabia is very huge as most of construction in Saudi Arabia is made of concrete or has concrete [22]. Thus, optimizing concrete mixture design is highly requested to be in line with sustainability initiative in the Vision 2030. The Tarantula Curve has shown great success in improving the concrete sustainability by reducing the cement content and still producing concrete that is workable, durable, and strong. Research has been conducted to validate the Tarantula curve boundaries based on fresh properties only such as workability. However, this work not only aims to validate the boundaries in the fresh state of concrete, but also, aims to measure the hardened properties such as the compressive strength to validate the boundaries using a variety of aggregate sources in Saudi Arabia.

Since the ACI 211 concrete design method is widely used in concrete production factories in Saudi Arabia, a comparison was made between the ACI 211 method and the Tarantula Curve method in terms of workability, compressive strength, and cost. Recommendations and further future framework will be given.

2 Methodology

2.1 Materials

In this project, materials from various sources were used to design concrete mixtures. Coarse aggregate and intermediate aggregates were brought from Riyadh and Jeddah Regions. One source of fine aggregates was from Jeddah and the other sources were from various locations within Riyadh region. Table 1 shows the aggregates properties and their source.

Table 1 -Materials used in the study with their properties

Materials ID	Specific Gravity	Absorption %	Source
Coarse aggregates			
RUH 20 mm	2.608	1.86	Rumah (Riyadh)
RUH 10 mm	2.606	2.05	Rumah (Riyadh)
Jed 20 mm	2.74	0.82	Jeddah
Jed 10 mm	2.75	0.73	Jeddah
Fine aggregates			
Jed sand (JS)	2.81	1.33	(Jeddah)
Dune Sand (D.S)	2.61	0.62	Sulay (Riyadh)
Coarse sand SRCC (C.S)	2.613	1.11	Sulay (Riyadh)
White Sand (W.S)	2.72	0.96	Rumah (Riyadh)
Red Sand (R.S)	2.51	0.58	Rumah (Riyadh)
Alkharj Sand (A.S)	2.70	1.00	Alkharj (Riyadh)
North west Sand (NW.S)	2.60	1.09%	Western (Riyadh)

Yamama cement [23] was used in the mixtures along with 20% Fly ash class C [24] replacement. An admixture PC175 [25] was used in the mixtures as a mid-range water-reducer.

2.2 Sieve analysis

The aggregates were sieved according to the ASTM C 136 and the percent passing chart below in Fig. 4 shows the sieve analysis for the aggregates used in this project.

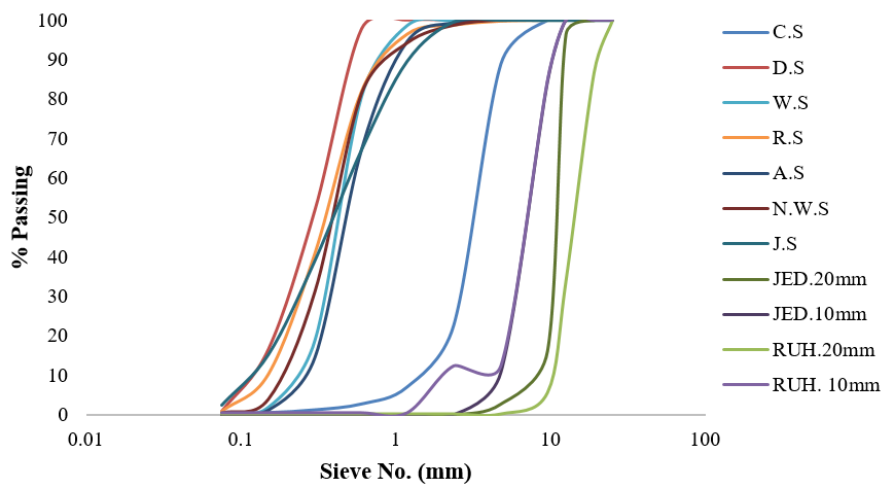


Fig. 4 -Sieve analysis of the coarse and fine aggregates expressed in % passing

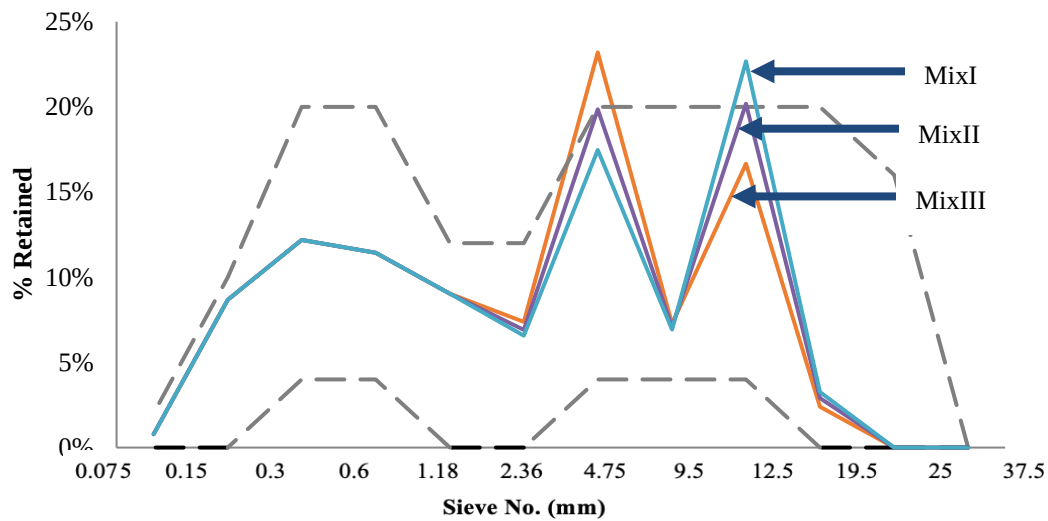


Fig. 5 – Mixtures with different gradations to evaluate the Tarantula Curve Coarse aggregate boundaries (using materials from Jeddah region).

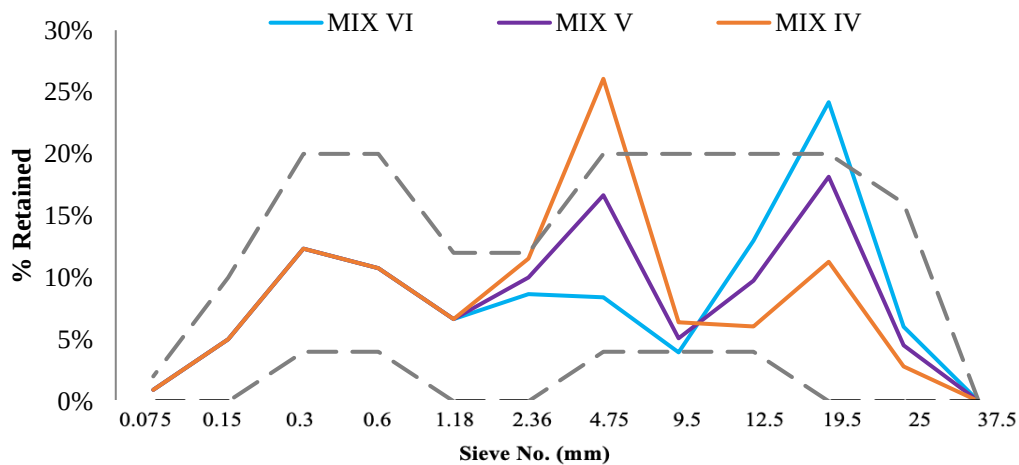


Fig. 6 – Mixtures with different gradations to evaluate the Tarantula Curve Coarse aggregate boundaries (using materials from Riyadh region)

To evaluate the Tarantula Curve boundaries using materials from Saudi Arabia, first, concrete mixtures were designed to investigate the effects of exceeding the coarse aggregate sieve limits. Fig. 5 shows concrete mixtures prepared using materials from Jeddah region while Fig. 6 shows concrete mixtures prepared using materials from Riyadh region. The mixture designs are attached in Table A1 in the appendix.

All the mixtures had a water-to-cementitious materials ratio (w/cm) of 0.45 and a fixed paste volume to allow the comparison between the workability and compressive strength of various combined gradations.

Then, another set of mixtures were proportioned to evaluate the effect of exceeding the fine aggregates sieves limits, Shown in Fig.7 and Fig. 8. These mixtures were prepared from materials brought from Riyadh region. Note that different sand source was used in each figure and the mixture designs are attached in Table A1 in the appendix.

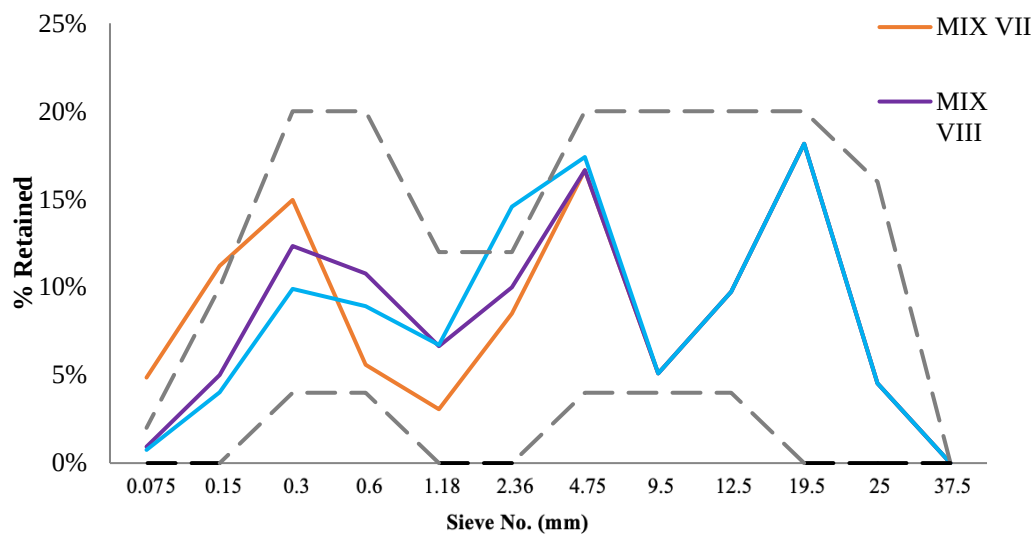


Fig. 7 – Mixtures with different gradations to evaluate the Tarantula Curve Fine aggregate boundaries (DS +CS sand sources).

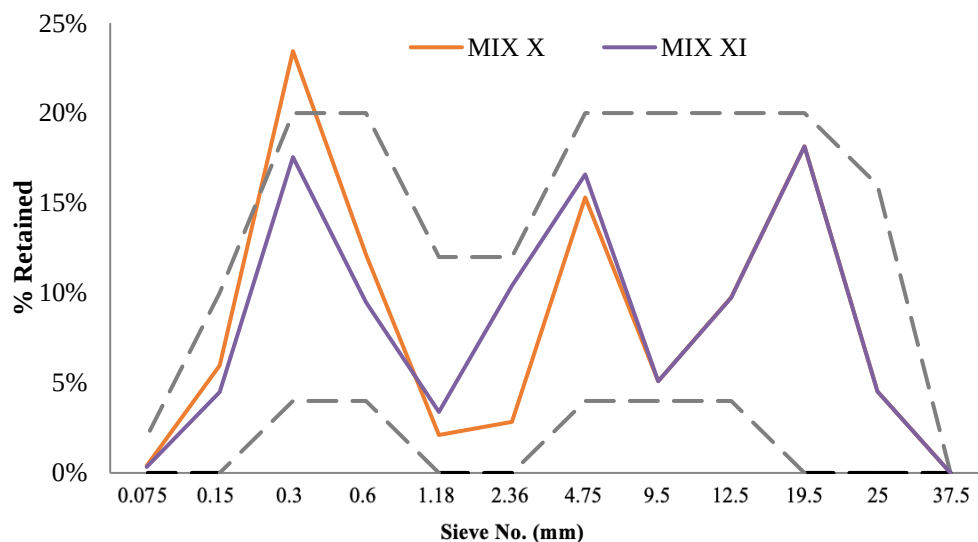


Fig. 8 – Mixture with different gradations to evaluate the Tarantula Curve Fine aggregate boundaries (A.S +CS sand sources).

All the mixtures were designed with a water-to-cementitious materials ratio (w/cm) of 0.45 and a fixed paste volume to allow the comparison between the workability and compressive strength of various combined gradations.

Since it is common to design concrete mixtures in Saudi Arabia using the ACI-211, a comparison between concrete mixtures designed by the ACI-211 method and the Tarantula Curve method was made in terms of workability, compressive strength, and cost as shown in Table 2. The mixtures were designed with a w/cm ratio of 0.45 and the WR dosages were added incrementally as needed to reach a slump between 100 mm- 200 mm with a maximum dosage of 1.68 L/m³.

Table 2 – Mixtures designed by the Tarantula Curve and the ACI-211 design method using different sand sources

Material	TC1	ACI 1	TC2	ACI2	TC3	ACI3	TC4	ACI4	TC5	ACI5
Cement	268	365	268	365	268	365	268	365	268	365
Fly ash	67	91	67	91	67	91	67	91	67	91
Water	151	205	151	205	151	205	151	205	151	205
Ruh20 mm CA	602	638	486	609	498	637	498	618	623	633
Ruh10 mm CA	407	343	522	327	534	343	534	333	385	364
DS.	648	226	—	—	305	447	—	—	—	—
CS.	162	439	148	257	—	—	—	—	208	167
RS.	—	—	638	438	—	—	291	210	—	—
WS.	—	—	—	—	486	210	486	447	—	—
NW.S	—	—	—	—	—	—	—	—	626	526
WR.	1.68	1.68	1.68	0	1.68	0	1.68	0	1.68	1.68

2.3 Mixing procedure

The aggregates were collected from the stockpiles and brought into a lab where the temperature is controlled at 25 °C (73 °F) for a minimum period of 24 hours before mixing. Then, the aggregates were placed in a mixer and spun for taking representative samples to do moisture correction. At the time of mixing, all of the aggregates were loaded in the mixer along with 2/3 of the water amount and mixed for three minutes to produce homogeneous materials and achieve the saturated surface dry condition (SSD). Subsequently, the cementitious materials were added in the mixer along with the remaining water and spun for three minutes. Two minutes is counted for the concrete to rest in the mixer and the sides of the mixer were scraped. The admixtures were added After the rest period and the concrete was mixed for another three more minutes.

2.4 Concrete testing

2.4.1 Slump test

The slump test is a well-recognized test for measuring both concrete workability and homogeneity. It is conducted as per the ASTM C143 [26] where the cone is filled in three layers of freshly mixed concrete, then, each layer is rodded 25 times. After finishing off the surface of the cone, the cone is lifted vertically upward in three seconds and the concrete slump due to its own weight and the slump is determined.

2.4.2 Concrete compressive strength test

The concrete compressive strength is the ability of concrete to carry the loads on its surface without any crack or deflection. In this project, cylindrical molds, 152mm – 305 mm, were used to produce the concrete samples. These samples were cured in water-tank and tested at 7days and 28 days as per the ASTM C39 [27].

2.4.3 Comparative analysis of concrete cost

Optimizing the concrete design results in a reduction in the cost of concrete and a production of good quality concrete. In this project, a set of concrete mixtures was designed by the Tarantula Curve. Then, another set of concrete mixtures was designed by the ACI-211, with the same materials used in the first set of mixtures as discussed in section 2.3. Table 3 shows the cost in Saudi Riyal (SAR) of concrete ingredients per kilograms (kg).

Table 3 -Cost of the materials used in making concrete mixtures

Material	Price
Cement	0.279 sr/kg
Fly ash	0.15 sr/kg
Water	0.1 sr/kg
20 mm CA	0.107sr/kg
10 mm CA	0.107sr/kg
DS.	0.0982sr/kg
CS.	0.112sr/kg
RS.	0.1sr/kg
WS.	0.1sr/kg
NW.S	0.1 sr/kg
WR.	0.1875sr/kg

3 Result and discussion

In Saudi Arabia, the sand is available everywhere in enormous amounts. However, most of it is either too fine to use for concrete or too coarse. Finding good quality sand with a good gradation is very challenging. Thus, concrete producers tend to combine coarse sand with fine sand to achieve acceptable sand gradations and meet the ASTM C33 limits. They are using trial and error batches to determine the best combination for each stockpile and every time the aggregate is changed, more trials should be conducted. The Tarantula Curve offers optimized gradations by providing boundaries for sieve size in which when they are exceeded, it tells you about its impact on the mixture. Also, it provides criteria for fine sand and coarse sand as mentioned earlier.

3.1 Testing coarse aggregate boundaries

Three mixtures were designed to evaluate the effects of exceeding the coarse aggregates boundaries. The first mixture was designed to exceed the sieve size 12.5mm (1/2") and the second mix was designed to satisfy the limits whereas the third mix was designed to exceed the sieve size 4.75mm (#4) limit. The results of these mixtures are Tabulated in Table 4.

Table 4 -Results of mixtures for coarse aggregate boundaries evaluation

Mixture	Slump (mm)	Compressive strength (MPa)	
		7 days	28 days
MIX I (12.5mm sieve exceeded)	220	24	35
MIX II (Within limits)	180	29	39
MIX III (4.75mm sieve exceeded)	190	25	35
MIX IV (12.5mm sieve exceeded)	200	21	32
MIX V (Within limits)	173	27	38
MIX VI (4.75mm sieve exceeded)	160	24	35

It can be noticed that even though the slump results are the highest in Mix I and Mix IV where it exceeded the limit of the sieve size 12.5 mm (1/2"), the mixture was observed to have high segregation. Fig. 9 shows the segregation occurred in MIX I.



Fig.9 -Segregated concrete in MIX I

For Mix III and Mix VI, where the sieve size 4.75 mm (#4) was exceeded, harsher mixtures were obtained with some segregation. These results and observations were made with materials obtained from Saudi Arabia. They match the findings in Ghazal et al. where when the coarse aggregate boundaries were exceeded, segregation occurs in the mixtures [28].

Regarding the compressive strength, it can be noticed that the compressive strength decreased when the combined aggregate gradation goes above the coarse aggregate limits specified by the Tarantula Curve. This is true for both the 7 days and 28 days compressive strength as shown in Fig. 10. It is found that these boundaries not only ensure the workability of concrete, but they also ensure the compressive strength of concrete.

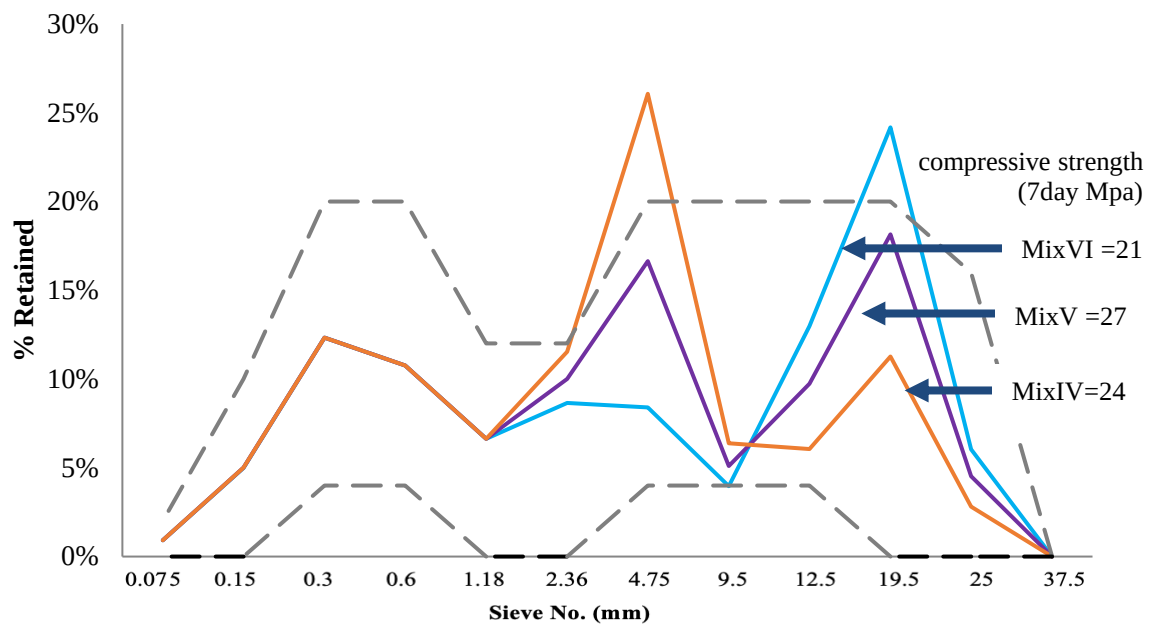


Fig.10 -Compressive strength of mixtures with different gradations to evaluate the Tarantula Curve coarse aggregate boundaries.

3.2 Testing fine aggregate boundaries

As for the fine aggregate sieve boundaries examining, the data is tabulated in Table 5.

It can be seen from Table 5 that the slump values of MIX VII and MIX VIII have the same slump value. However, the performance in the compressive strength is higher in MIX VIII where the limits were satisfied in both 7-days and 28-days. MIX IX where the sieve size 2.36 mm (#8) was exceeded showed lower slump value as well as lower compressive strength results in comparison to MIX VIII where the limits were satisfied.

This suggests that exceeding boundaries in the Tarantula Curve would not only lower the concrete workability [8], but also, lower the concrete compressive strength in both 7-days and 28-days as shown in Fig. 11. The Tarantula Curve boundaries was proved to provide insight about the concrete workability [8, 15-17], but also can provide insight about the compressive strength as well.

Table 5 –Mixtures for fine aggregate boundaries evaluation

Mixture	Slump (mm)	Compressive strength (MPa)	
		7 days	28 days
MIX VII (Out sieve 75 μ m, 0.15 mm)	150	26	37
MIX VIII (Within limits)	150	29	39
MIX IX (Out sieve 2.36 mm)	140	24	30
MIX X (Within limits)	60	22	30
MIX XI (Out sieve 0.3 mm)	55	21	29

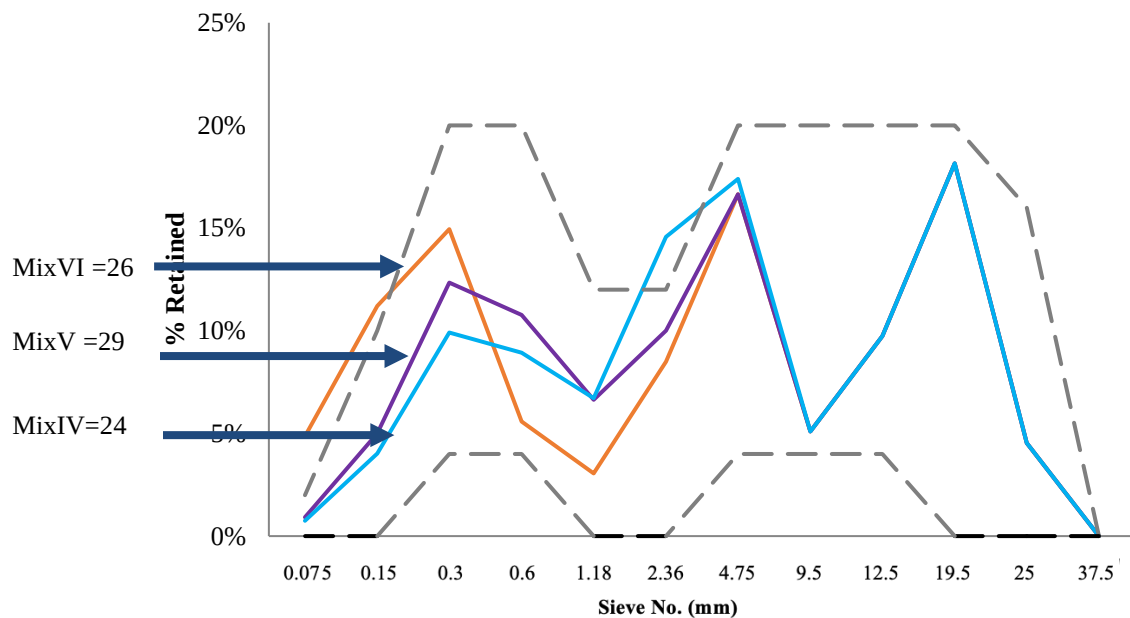


Fig.11 - Compressive strength of mixtures with different gradations to evaluate the Tarantula Curve Fine aggregate boundaries.

For the sieve size 0.3 mm (#50), Cook et al found that exceeding the limit for this sieve did not change much in workability and the mixture with high materials retained on this sieve exhibit very smooth surface finish [8]. MIX X and MIX XI in Table 5 showed very similar performance even though MIX XI exceeded the suggested limits in terms of workability. This matches the findings found in Cook et al research. To support their similarity in workability performance, it can be seen that the compressive strength in both mixtures is almost exactly the same.

3.3 Comparing the Tarantula Curve to the ACI 211 method

Optimizing aggregate gradation not only helps with the workability behavior and producing cohesive mixtures, but it also helps in saving cement by reducing the paste required to achieve acceptable workability. Several mixtures with different gradations and fine aggregate sources were designed by the ACI-211 method and the Tarantula Curve method and their results are shown in Table 6.

Based on the slump data and observation, it can be noted that the ACI-211 mixtures have higher slump values, (design range was 150 mm – 200 mm), these mixes did not require any water-reducing admixtures due to the high paste content. The cement content used in the ACI-211 mixture was **364 kg/m³** (k in small letter). However, the Tarantula Curve required cement

content of **268 kg/m³** and the use of mid-range-water-reducing admixture to achieve flowable concrete. In general segregation was observed when designing the concrete mixtures by the ACI-211 method, an example is shown in Fig. 12. This is due to the poor gradations of the individual sand sources and the FM. cannot detect which sieve might cause the issue.

Table 6 -Comparison of slump and compressive strength of mixtures designed by the ACI 211 and the Tarantula Curve

Sand source	Mix design method	Slump (mm)	Compressive strength (MPa)		Comments
			7days	28days	
DS + CS	ACI-211	190	20	29	Good mix
	Tarantula Curve	140	27	38	Good mix
RS + CS	ACI-211	270	13	20	High segregation
	Tarantula Curve	160	26	32	Good mix
DS + WS	ACI-211	240	17	25	Slight segregation
	Tarantula Curve	235	21	31	Good mix
RS + WS	ACI-211	240	17	24	Slight segregation
	Tarantula Curve	170	24	31	Good mix
NW.S + CS	ACI-211	135	26	30	Good mix
	Tarantula Curve	130	28	37	Good mix



Fig.12 -Segregation occurred in the ACI211 mixture (NW.S + CS)

Many iterations and trial batches are required to achieve the desired concrete performance when designing by the ACI-211, especially with poor grading aggregates. However, with the Tarantula Curve boundaries, it was not as challenging as it was in the ACI-211 method to evaluate the combined gradations of the mixtures and locate the issues that caused the poor workability occurred in the ACI-211 mixes and solve them.

Regarding to the compressive strength comparison between the two mix design methods, based on Table 6, the Tarantula Curve provided mixtures with higher compressive strength, about 35%, in comparison to the mixtures from the ACI-211 in both the 7-day and 28-day testing periods. Keep in mind that the Tarantula Curve mixtures had cement content of approximately 27% less than the ACI-211 mixtures.

3.4 Cost analysis

To determine the economical perspective of designing concrete mixture by using the Tarantula Curve and the ACI-211 methods, Table 7 shows the cost of each mixture designed by the mentioned methods per cubic meters. It can be observed that the Tarantula Curve mixtures have lower cost in comparison to the ACI-211 mixtures. A concrete producer can save approximately on average 6.0 % of concrete cost by using the Tarantula Curve method (18 SAR/m³). Optimizing the aggregate gradations in the Tarantula Curve mixtures helped decrease the cementitious materials content by approximately 27% and thus the cost.

Table 7 - Analysis for computing the mixture cost per cubic meter for the Tarantula Curve and the ACI 211 methods

Material	TC1		ACI1		TC2		ACI2		TC3		ACI3		TC4		ACI4		TC5		ACI5	
	weight (kg)	Cost SAR	weight (kg)	Cost SAR	weight (kg)	Cost	weight (kg)	cost	weight (kg)	Cost	weight (kg)	Cost	weight (kg)	cost	weight (kg)	cost	weight (kg)	cost	weight (kg)	cost
Cement 0.279 sr/kg	268	74	364	101	268	74	364	101	268	74	364	101	268	74	364	101	268	74	364	101
Fly ash 0.15. sr/kg	67	10	91	13	67	10	91	13	67	10	91	13	67	10	91	13	67	10	91	13
Water 0.1 sr/kg	151	15	205	20	151	15	205	20	151	15	205	20	151	15	205	20	151	15	205	20
20 mm CA 0.107. sr/kg	486	52	637	68	486	52	609	65	498	53	637	68	498	53	618	66	498	53	633	68
10 mm CA. 0.107. sr/kg	522	56	343	37	522	55	327	34	534	57	343	36	534	57	333	35	534	57	364	39
DS. 0.0982. sr/kg	463	45	439	43	—	—	—	—	305	30	447	43	—	—	—	—	—	—	—	—
CS. 0.112 sr/kg	358	40	226	25	148	16	257	28	—	—	—	—	—	—	—	—	207	23	167	19
RS. 0.1 sr/kg	—	—	—	—	638	63	438	43	—	—	—	—	291	29	210	21	—	—	—	—
NW.W 0.1sr/kg	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	625	62	526	52
WS. 0.1sr/kg	—	—	—	—	—	—	—	—	486	48	210	21	486	48	447	44	—	—	—	—
WR. 0.1875sr/kg	1.68	—	0	0	1.68	0.32	0	0	1.68	0.31	0	0	1.68	0.31	0	0	1.68	0.3	1.68	0
Total cost	292		307		288		313		289		305		288		303		294		312	
Difference	15				25				16				15				18			

4 Practical significant

Concrete constructions have been increasing dramatically. New cities and large projects require huge amount of concrete. extensive concrete production will not only cause deficiency in the raw material, but also it will harm the environment. Thus, utilizing a concrete proportioning method that will produce concrete with less amount of cement and still maintain workability, strength, and durability is highly desired. This will not improve the cost of concrete, but also the sustainability of the concrete. This work validates critical sieve sizes on the Tarantula Curve by measuring the compressive strength of a variety of combined gradations using local materials. This work shows a comparison between the widely used concrete mix design method in Saudi Arabia, the ACI 211 method, and the Tarantula Curve method. It is found that the Tarantula Curve method can produce concrete with 35% more compressive strength than the ACI 211 method. The cementitious content in the Tarantula Curve mixtures is decreased by 27% in comparison to the ACI 211 mixtures. This reduction in cement content saves approximately 6% of concrete cost per cubic meter. The durability comparison between the two methods can show essential information. Also, testing samples using SEM or XCT could reveal behavior differences in the material performance which is an area of future study.

5 Conclusion

Concrete durability and sustainability can be achieved by optimizing aggregate gradations. This optimization process can reduce the cementitious materials required to produce concrete that is still workable and strong. The Tarantula Curve proportioning method was used to proportion local aggregates in Saudi Arabia. This was done to determine whether the boundaries are applicable with the use of local materials. In addition, a comparison between the Tarantula Curve and the ACI 211 method was made. The following conclusions were drawn from the study.

It was confirmed that exceeding coarse aggregates boundaries (12.5mm and 4.75mm) provided by the Tarantula Curve produced mixtures with segregation and poor workability when local materials were used. In addition, poor workability was obtained as the sieve sizes 75 μ m, 150 μ m, and 2.36mm limits were exceeded for the fine aggregates' boundaries, which validates the developed limits using local aggregates. In this study, it was found that the compressive strength of concrete was affected by the gradation of the aggregates. When exceeding the sieve sizes 12.5mm and 4.75mm in the coarse aggregates side in the Tarantula Curve, the compressive strength decreased. Similarly, exceeding the sieve sizes 75 μ m, 150 μ m, 2.36mm in the fine aggregates side in the Tarantula Curve resulted in a reduction in the compressive strength. The Tarantula Curve not only ensured workability performance of concrete mixtures, but also ensured the compressive strength performance as well.

When designing concrete mixtures using the ACI 211 method, segregation was observed in the mixtures due to the lack of good quality fine aggregate gradations in Saudi Arabia. Mixture design would require many trial and error batches to achieve the acceptable design. The ACI 211 mixtures required approximately 27% more of cementitious materials compared to the Tarantula Curve method. In terms of economy, the ACI 211 mixtures cost 6% more than the mixtures designed by the Tarantula Curve per cubic meter. In terms of compressive strength performance, the Tarantula Curve mixtures produced mixtures with compressive strength 35% higher than the ACI 211 mixtures.

This work provides further validation of the Tarantula Curve boundaries by testing not only workability, but mainly the compressive strength of concrete mixtures. It also compares two concrete mix design methods in terms of workability, strength, and cost. This is an essential step in investigating the approach that provides more sustainable concrete with cost efficiency.

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