OPTIMIZATION OF AGGREGATE GRADATION

&

CONCRETE MATURITY

By

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CONCRETE MATURITY

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CHAPTER I

INTRODUCTION

The goal of this study is to provide a mixture design that needs a minimum amount of cement content for pavement concrete. The reduction in cement content was achieved by using different aggregate gradations. Maturity curves were developed for the final design mixtures as inputs for computer models that describe the long term performance of the materials. This work was funded by a grant from the FHWA for the Highways for Life Program. The mixture developed has been used on FM 1938 near Ft. Worth, TX with satisfactory performance.

The development of concrete strength with time was the object of concrete maturity in chapter II. The concrete maturity chapter consists of two main subjects; first one is illustrating the relation between the histories of hydration temperatures of concrete with respect to gained strength when varying the mixture design under same curing conditions, while the second one is about the predicting concrete strength in means of maturity method.

Chapter III is dealing with optimization of aggregate gradation in order to reduce the paste volume required to fill the cavities between aggregate particles. Methods of aggregate gradation were adopted to acquire good particle distributions and the nominated gradations were checked in regard of best particles packing. The aggregate Packing density was evaluated by aggregate dry unit weight.

The mixture design is varied using different aggregate gradations in order to maintain a good workability, good response to the vibrator with a good reduction in cement content. Both

Chapters II and III are consisting of an introduction, materials and adopted methods, results, discussion, and conclusions. Chapter IV was a summary of the final conclusions of the previous chapters.

CHAPTER II

CONCRETE MATURITY

2.1 INTRODUCTION

2.1.1 Overview

The motivation behind maturity is the need for new methods to estimate concrete strength with accurate results while minimizing physical testing. The aim behind this idea was to model the effect of accelerated curing on concrete strength [1]. Later this led to the establishment of the maturity method in 1951 by Nurse and Saul [1].

The maturity method is widely used because of its simplicity and accuracy in prediction of concrete strength.

The maturity theory has two main aspects: first is application of the maturity to estimate in place concrete strength, as described by ASTM C 1074[2], and the second is projecting long term concrete strength by measuring the early age concrete strength which is adopted by ASTM C 918 [3].

The study includes the effect of material proportions on concrete maturity with the associated compressive strength. The study also includes the projecting of long term concrete strength by means of concrete maturity according to ASTM C918.

Maturity is an approach to predict the strength of the in-place concrete under any temperature conditions. ASTM C1074 defines the maturity as “a technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strength if they attain equal values of maturity index”.

A.G. Saul defined the maturity as, “concrete of the same mixture at the same maturity has approximately the same strength whatever combination of temperature and time goes to make up that maturity” [1]. In other words, if we have same maturity for two mixtures with the same mixture design, the strength of concrete will be the same whatever the combination of time and temperature are for these two mixtures.

2.1.2 Advantages and disadvantages of maturity method

Maturity is an accurate method to predict concrete strength. According to ASTM C1074, in the field this method should be accompanied with another testing method to double check the concrete strength.

The Maturity method saves time and money by the accurate prediction of concrete strength to remove slip forms, cut and saw timing and open pavement to traffic. This method saves money by reducing the samples required to test. The strength of concrete estimation is also important to the new construction of buildings and roads. Maturity is useful for operating timing of pre-stressed concrete [4]. The method can estimate the strength of concrete at any age.

The negative side of the maturity method is that a complete hydration should continue without ceasing otherwise predictions will be incorrect. This method will not take into account some field actions, like inadequate vibration and insufficient curing. Every mixture has its own unique maturity. So strength maturity curve should be established for every individual mixture [4].

2.1.3 Maturity-index and equivalent age factor

This method provides a procedure for estimating concrete strength by means of the maturity index or equivalent age factor. Maturity index is expressed in terms of the temperature-time factor (°C –hour or ^{0}F-hour) according to the Saul –Nurse Function. Another equation is the equivalent age at a specified temperature (Arrhenius equation, which has been developed by Hansen and Pederson later in 1977) which is expressed in terms of equivalent age (days or hours).

Maturity is a method to assess the in- place concrete strength. According to ASTM C1074, in order to determine the in place concrete strength, the maturity index which is the term referring to concrete maturity, is calculated according to Nurse-Saul or Arrhenius equation:

1- temperature-time factor or maturity index by Nurse –Saul equation [1]:

$$M(t) = \sum (T - T_0)\,\Delta t \qquad (2\text{-}1)$$

Where:

M (t) = the temperature-time factor at age t, (°C – hours) or (^{0}F – hours),

Δt = a time interval, days or hours,

T = average concrete temperature during time interval, °C, or ^{0}F, and

To = datum temperature, °C or ^{0}F

To; the lowest temperature at which strength gain is observed (Figure 2-1). This temperature can be calculated according to ASTM C1074 method. This temperature was adopted by Saul to be 0°C, and then later adjusted to a value of -10°C [1]. Other researchers like Plowman recommended being -12°C [5]

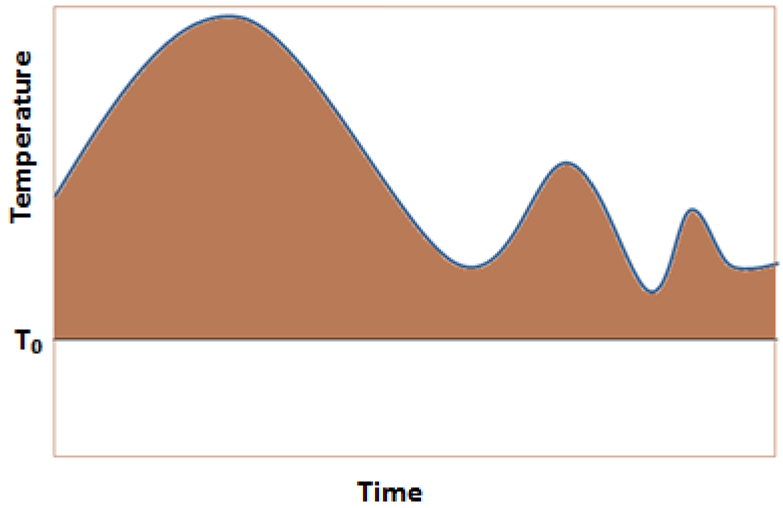


Figure 2-1: Datum temperature

The Nurse equation can be expressed in terms of equivalent age at a reference curing temperature:

$$te = ((T - To) / (Tr - T_0))\, \Delta t \qquad (2\text{-}2)$$

Where:

te = equivalent age at a reference curing temperature. It represents the duration of the curing period at the reference temperature that would result in the same maturity as the curing period at different temperatures.

Tr =reference curing temperature

2- Arrhenius Equivalent age at a specified temperature by Hansen-Pederson (Arrhenius) [6] [7]:

$$te = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T} - \frac{1}{273+Tr}\right]}\, \Delta t \qquad (2\text{-}3)$$

Where:

te = equivalent age at a reference curing temperature Tr, days or hours.

T = average temperature of concrete during time interval Δt, °C

Tr = reference temperature, °C

E= activation energy, J/mol

R= universal gas constant, 8.3144 J/ (mol K)

Δt = time interval, days or hours.

2.1.4 Maturity equations for estimating in place concrete strength

The concept of concrete maturity has been expressed in the equation of Saul and Nurse, and then many equations appeared after that.

The maturity index been evaluated in many equations. The equations for evaluating the maturity index are as following [1]:

1- Nurse- Saul; is a linear equation which overestimates the maturity index for temperatures below 20°C, and underestimates the maturity index (age conversion factor) for temperatures above 20°C (early age).The maturity index is:

$$te=\sum \alpha \, \Delta t \qquad (2\text{-}4)$$

$$\alpha= (T-T_0)/ (Tr-T_0) \qquad (2\text{-}5)$$

Where:

te =equivalent age factor

T = average Temperature °C or ^{0}F

To = datum temperature (-10°C or 14^0F)

Tr = Reference Temperature (20°C or 68^0F)

Δt =time interval (1/2hour-1 hour)

α= age conversion factor. It converts the curing interval Δt into equivalent curing temperature at the standard reference temperature [1].

N.J. Carino does not recommend using this equation, because it overestimates the maturity index less than 20 °C. This means for ages after 6 days this equation is giving us inaccurate results [8].

2- Rastrup equation; is an exponential equation which is based on the physical chemistry ;(reaction velocity is doubled if the temperature is increased by 10°C) [9].

$$te= \sum 2^{(T-Tr)/10}\, \Delta t \qquad (2\text{-}6)$$

For high concrete temperatures this equation yields higher values [10].

3- Weaver & Sadgrove; is another nonlinear equation [11]. This equation gives a better strength estimation for a low maturity value than Saul & Nurse does. But for later maturities the Nurse and Saul equation will give more accurate results [12].

$$te= \frac{\sum_{(T+16)}2}{1296}\, \Delta t \qquad (2\text{-}7)$$

4- Freiesleben Hansen and Pederson (Arrhenius) [7]; is another nonlinear equation, expressed in terms of absolute temperature. The curve will depend on the value of the activation energy value, in which this value will be as following, according to Freiesleben Hansen and Pederson:

$$te = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T} - \frac{1}{273+Tr}\right]} \Delta t \quad (2\text{-}8)$$

For T≥20°C E=33500 J/mol

For T<20°C E=33500+1470(20-T) J/mol

This equation is developed from the Arrhenius equation. It gives the best estimation of strength among a wide range of temperatures [13].

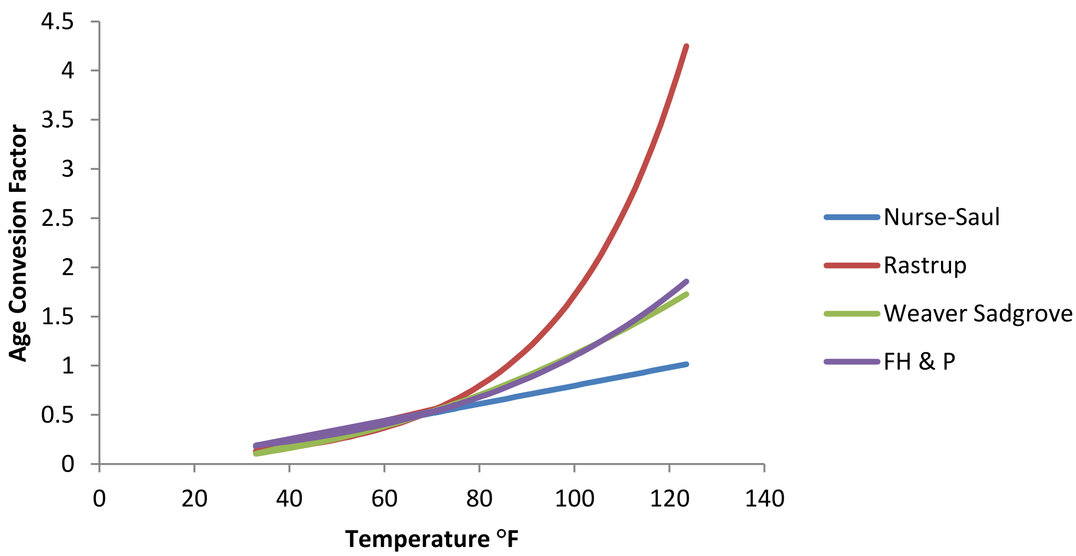


Figure 2-2: Maturity equations

Comparing these equations is shown in Figure 2-2 for a certain mixture design, and under different curing temperatures.

2.1.5 Maturity equations for predicting strength

The previous section dealt with the maturity as a means to estimate the in-place concrete strength depending on the hydration temperature history. Only one unique curve would represent the maturity –strength relation for a certain mixture. Any changing in mixture design will lead to a different curve or relation [14]. The other useful side of the maturity method is the ability to estimate the long term concrete strength (28 days or more). In this the relation of maturity and concrete strength (28 or 56 days) can be established according to ASTM C1074. Based on the maturity-strength curve we can project the long term strength by measuring the strength of early age (24 hours) according to ASTM C918/C918M.

The main strength –maturity equations can be classified as following:

1- Exponential equation, proposed by Nykanen in 1956 [15]:

$$S=S_\infty (1 - e^{kM}) \qquad (2\text{-}9)$$

Where:

S_∞ = limiting strength.

S= compressive strength.

M= maturity index.

k= constant.

This equation is dealing with a constant (k) whose value is depending on the initial rate of strength development during the hydration in the early age period. This is dependent on water-cement ratio and the kind of cements used [15].

2- Logarithm equation set by Plowman [5]:

$$S=a + b \log (M) \qquad (2\text{-}10)$$

Where:

a and b are constants

Logarithm equations or linear equations adopted by the ASTM C918 to predict the long term strength of concrete by measuring the early age strength. Logarithm of maturity index is represented on the horizontal axis, while the vertical axis is the concrete strength gained from 12 hours till 28 days or more. The constants (a) and (b) value are dependent on cement type and water-cement ratio used in the mixture. The negative side of this equation is the unlimited increasing value of strength with respect to maturity index as it considers the relation as a line instead of curve [16].

3- Lew and Reichard improved Plowman equation to the following log–exponential equation [17]:

$$S = \frac{K}{1+D(\log(M-16.70))^{\wedge}b} \qquad (2\text{-}11)$$

In which (b) and (D) are constants depending on cement type and water-cement ratio, and (k) is the rate of strength also dependent on the water-cement ratio but less dependent on the cement type [14]. This improvement overcomes the negative side of the original logarithm equation by limiting the strength gain with increasing the maturity [17].

4- Hyperbolic equation proposed by Bernhardt in 1956 and developed by Chin [18]: [19]:

This theory was adopted by ACI, committee 229. The initial slope of the relation will control the shape of the hyperbolic curve [19]:

$$S=M/\ (1/A+M/S\infty) \qquad (2\text{-}12)$$

Where:

M=maturity index.

S_∞ = limiting strength.

A= initial slope of strength maturity curve.

The equation above was modified later by some studies to account for the effect of early maturity on strength development in which the hyperbolic equation considered that the strength starts from maturity (M) =0, while real strength starts after concrete has been set [21]. Adding a shifting value of maturity to the previous equation solved this issue [20]:

$$S = \frac{M - M_0}{\frac{1}{A} + \frac{M - M_0}{S\infty}} \tag{2-13}$$

Where:

M_0 = initial maturity in which strength starts > 0

5- Maturity-Heat of hydration equation, suggested by Freiesleben Hansen to correlate the heat of hydration with maturity according to the following equation [22]:

$$f = f_{cult}\, e^{-\left(\frac{\tau}{te}\right)^{\beta}} \tag{2-14}$$

Where:

fcult = limiting strength (psi)

te= equivalent age (hour)

τ = time constant (hour)

β = shape parameter

According to Carino; (This equation can model gradual strength development during the setting period and it is also asymptotic to a limiting strength) [8]. The time constant (τ) represents the time required to acquire 0.37 of the limiting strength. (1/ τ) represents the rate constant for this equation. The shape parameter (β) will affect the slope of maturity curve [8].

2.2 MATERIALS AND METHODS

2.2.1 Materials & mixture designs

2.2.1.1 Materials

Material properties used in this study and standard requirements are shown in Table 2-1

Table 2-1: Materials properties

Material	Type	Sp. Gr.	Requirements
1-Cement	Type l /TX.	3.15	ASTM C150
2-Flyash	Class F/ Martin Lake	2.5	ASTM C618
3-Corase Aggregate 1.5”	G3 /TX.	2.65	ASTM C127, ASTM C33
4-intermediate Aggregate	3/8”/ TX.	2.65	ASTM C127
5-Sand	TX.	2.65	ASTM C128, ASTM C33
6-Water	Tab water	1	ASTM C1602
7-Water Reducer	DARACEM 55	1.28	ASTM C494
8- Air entertainer	DARAVAIR 1400	1.02	ASTM C260

Maturity can be calculated by inserting temperature sensors and recording temperature over time. Maturity then can be calculated by Nurse-Saul equation or Arrhenius equation. An interval of 30 minutes was chosen to acquire accurate results.

2.2.1.2 Mixture designs

The materials used; and the mixture designs are listed in Table 2-2-a. The fresh and hardened concrete tests results are listed in Table 2-2-b.

Starting is with a small amount of cement binder of 423 b/cu yard (in mixture 1), with water cement ratio 0.45. Class F fly ash at 35% to the total cementitious materials. Coarse, medium, and fine aggregate sizes were used in first mixture. In the following mixtures (2, 3& 4); we increased the cementitious materials with 0.43 water cement ratio. The increasing of cementitious materials is combined with decreasing coarse aggregate used (without using 3/8" aggregate size).

Materials and quantities are the same in mixtures (3) and (4), but with increasing the water reducer in mixture (4).

Table 2-2 Mixture designs and results:

Mix #	Cement (lb./cy)	Flyash (lb./cy)	Binder (lb./cy)	G3 (lb./cy)	3/8" (lb./cy)	Sand (lb./cy)	Water (lb./cy)	w/c	EA (Oz/cwt.) DARAVAIR	WR (Oz/cwt.) DARACEM	Slump (in)	Unit wt. (lbs./ft^3)	Air %
1	275	148	423	1626.8	467	1265.6	190.35	0.45	0.45	6.1	1.5"	147.6	5
2	290.2	156.3	446.5	1941	0	1395	192	0.43	0.32	10.2	1.5"	148.4	5.7
3	320.8	172.7	493.5	1886	0	1355	212.2	0.43	0.62	5.2	4.4"	144.3	6.9
4	320.8	172.7	493.5	1886	0	1355	212.2	0.43	0.50	9.2	3.4"	143.5	7.3

a) Mixture designs and fresh concrete properties

Mix #	Compressive Strength& standard deviations for different ages															
	0.5 day		1 day		3 days		5 days		7 days		14 days		28 days		56 days	
	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)	Comp. (psi)	St. (psi)
1	480	19	1231	40	2661	31	3301	163	3603	18	4763	140	5857	166	6947	217
2	255	126	1776	16	3515	12	4090	51	4508	85	4704	65	6062	151	7075	93
3	404	13	1535	43	3147	120	3671	66	3891	129	3761	100	4677	94	5609	19
4	337	15	1613	54	3327	53	4100	147	4278	78	4754	71	5802	94	6678	131

b) Hardened concrete tests results

2.2.2 Methods

2.2.2.1 Effect of materials proportions on concrete maturity

We prepared two mixtures with exactly the same proportions to observe any deviations that may occur. We prepared 15 samples from each mixture according to the limitation of ASTM C 1074. A best fit curve for the two mixtures has been plotted to be the main curve; this relation will be the guide to estimate the in-place concrete strength for a certain value of maturity. In our research we applied the same curing conditions and monitored temperatures for every mixture with respect to time to observe the effect of the materials proportions on maturity-strength curve. We followed the following steps according to ASTM C1074:

1- Molding the samples according to ASTM C31 [23]. We insert sensors in two samples and record the temperature along the hydration age till 56 days.

2- Curing the samples in the fog room at a controlled temperature after 24 hours of casting.

3- Performing the compressive strength test for the specimens according to test method of ASTM C39/C39M [24]. The ages of testing were 12 hours, 1, 3, 5, 7, 14, 28, and 56 days respectively.

4- After measuring the temperature during the curing life for a time interval (Δt) equals 30 minutes, we calculated maturity index by Nurse -Saul function (temperature-time index).

5- Now we have data for both maturity index and strength for different hydration times. We plot the relation between the compressive strength and the maturity index by plotting the average maturity values on the horizontal axes, and plot the average compressive strength that we obtained for the corresponding maturity index on the vertical axes.

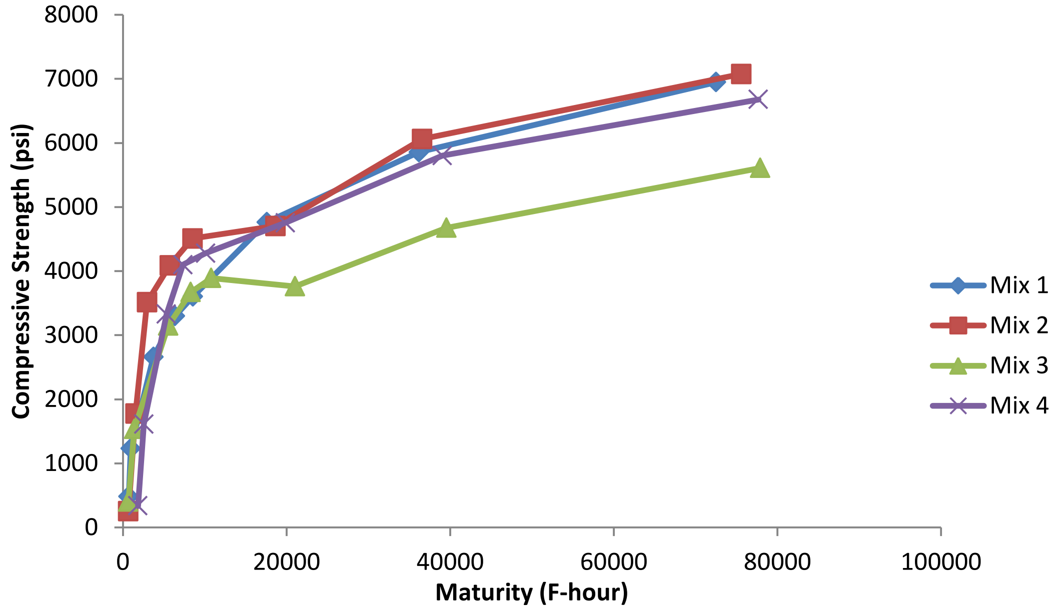


Figure 2-3: Maturity-strength development of the mixtures

2.2.2.2 Predicting later-age strength

According to ASTM C918, we applied the logarithm equation on mixture (4) in order to predict the long term concrete strength:

$$SM=Sm + b\ (\log M - \log m) \tag{2-15}$$

The above equation parameters were determined according to ASTM C918 procedure as following:

1- Mold and cure concrete samples according to ASTM C31/C31M.

2- Measure the sample temperature every 30 minutes until its aged 24 hours. The history of hydration temperatures is shown in Figure 2-5

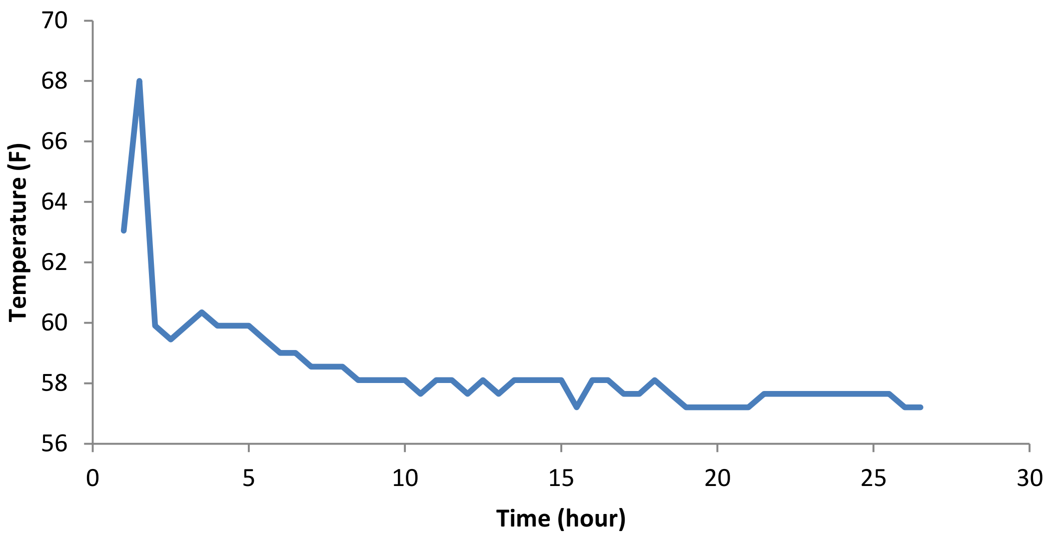


Figure 2-4: Temperature-time relation for mixture (4)

3- Compute the maturity index at an age of 24 hours after casting the concrete by Saul equation.

4- Compute the compressive strength at 24 days by running the compressive test according to ASTM C39/C39M on three concrete samples.

5- Maturity index for later age (M): Establish the maturity-strength curve according to ASTM C1074. We can determine the maturity index for the desired age (28 days) directly from the graph.

6- The line slope (b): convert the maturity index in step 3 into a log scale and determine the slope of the best fit line by regression analysis.

2.2.2.3 The constants in maturity-strength equations

2.2.2.3.1 Constants of the logarithm equation

The logarithm equation was adopted by ASTM C918 to predict the concrete strength by maturity method.

$$S=a + b \log (M) \qquad (2\text{-}10)$$

According to the specification of ASTM C918; the constant (a) represents the intersection of the maturity-strength line (in log scale) with the vertical axis which represents the compressive strength, while the constant (b) represents the slope of the mentioned line.

2.2.2.3.2 Constants of maturity-heat of hydration equation

This equation set by Freiesleben Hansen

$$f = f_{cult}\, e^{-\left(\frac{\tau}{te}\right)^{\beta}} \qquad (2\text{-}14)$$

According to Carino; the time constant (τ) represents the age at which the strength has reached 0.37 of the limited strength (Su) [8].

First step is to establish the relation between the equivalent age and compressive strength. Equivalent age was determined by the Arrhenius equation.

$$te = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T} - \frac{1}{273+Tr}\right]} \Delta t \qquad (2\text{-}3)$$

For T≥20°C E=33500 J/mol

For T<20°C E=33500+1470(20-T) J/mol

We calculated the equivalent age factor (te) according to Arrhenius equation. We plotted the equivalent age-strength in log scale with the associated compressive strength. From the graph we can estimate the value of equivalent age that corresponding to the 0.37 of the limited strength which represents the time constant (τ). The value of β (shape parameter), has expressed depending on the main equation:

$$f = f_{cult}\, e^{-\left(\frac{\tau}{te}\right)^{\beta}} \qquad (2\text{-}14)$$

Simplifying above equation into:

$\beta = \ln(\ln f_{cult} - \ln f) / (\ln \tau/te)$

β can be obtained by using excel sheet (try and error), then taking the average value of (β) for all ages.

2.3 RESULTS

2.3.1 Effect of materials proportions on concrete maturity

The compressive strength of every mixture has been plotted with respect to the corresponding maturity. The following points can be shown in Figure 2-5

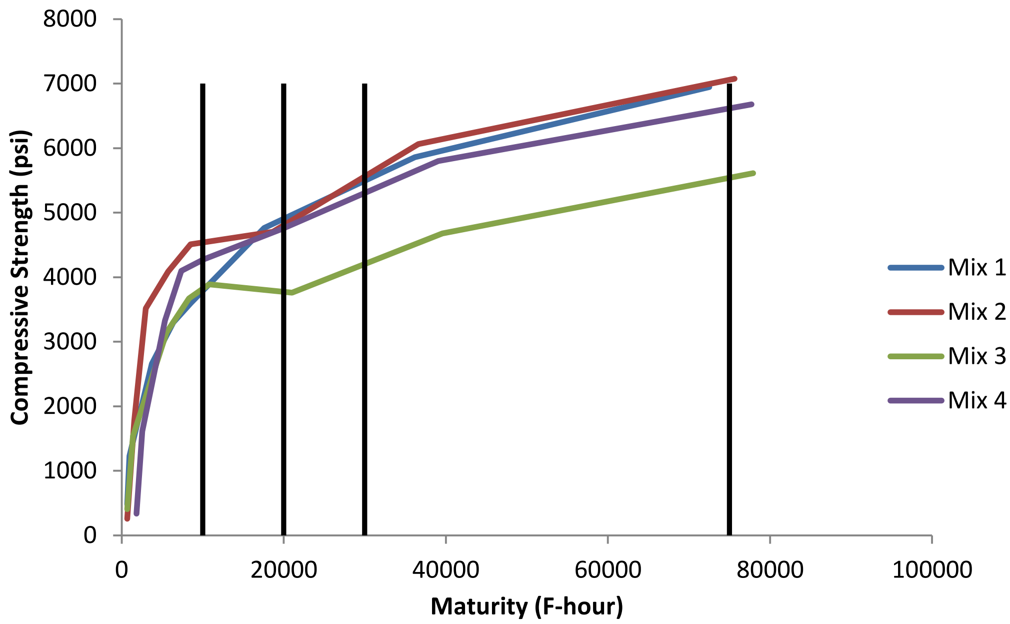


Figure 2-5: Zones of maturity-strength development

1- Zone (0 to 10000) F-hour; in this zone, mixture (2) followed by mixture 4 achieved the highest compressive strength, while mixtures (1) and (3) had almost the same maturity with lower corresponding compressive strength.

2- Zone (10000 to 20000) F-hour; in this zone, mixture (1) got the lowest compressive strength in the beginning of this zone, and then achieved the highest compressive strength in the end of this zone. Mixture (3) still has a low compressive strength with any maturity index.

3- Zone (20000 to 30000) F-hour; in the end of this zone we can see that mixture (2) acquired the highest compressive strength.

4- Zone (30000 to 75000) F-hour; no intersection between the mixture curves. Mixture (2) followed by mixture (1) recorded the highest compressive strength for any maturity index within this zone.

2.3.2 Predicting later-age strength

Following figure is showing the maturity index in log scale with respect to the compressive strength for mixture (4).

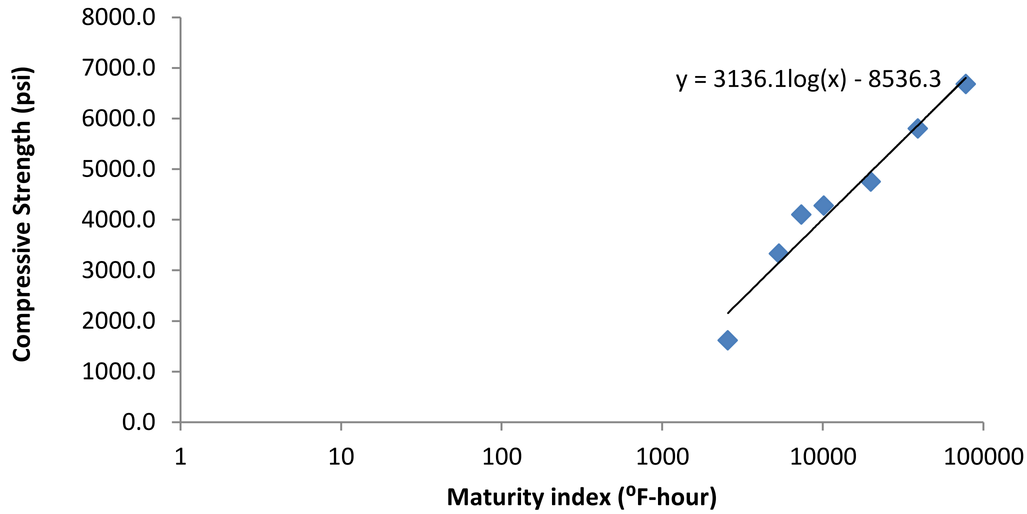


Figure 2-6: Maturity (log scale)-strength relation for mix (4)

The obtained values of the logarithm parameters are shown in Table 2-3

Table 2-3: Predicted strength result

b	Compressive strength (psi)	maturity (°F-hour)	Compressive Strength (psi)	
psi/°F/hour	Sm	m	projected(SM)	actual
3136.0	1272.0	1068.0	6174.0	5802.0

2.3.3 Constants of the maturity-strength equations

1- Constants of the logarithm equation

The following maturity-strength relations were obtained for the four mixtures:

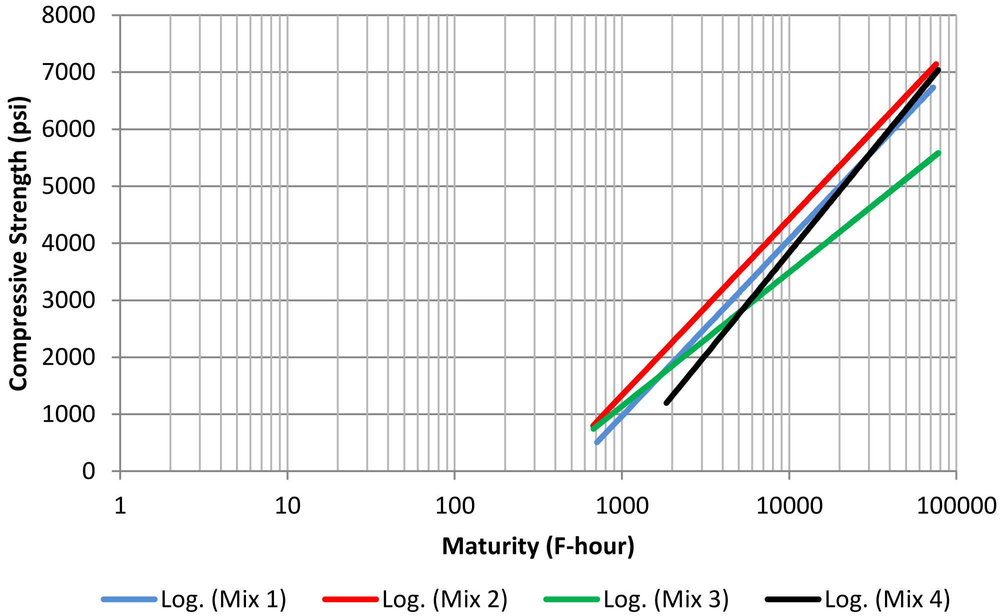


Figure 2-7: Maturity-strength curves (log scale)

2- Constants of the Hansen equation

The following Figure is showing the (equivalent age-strength) curves for the mixtures

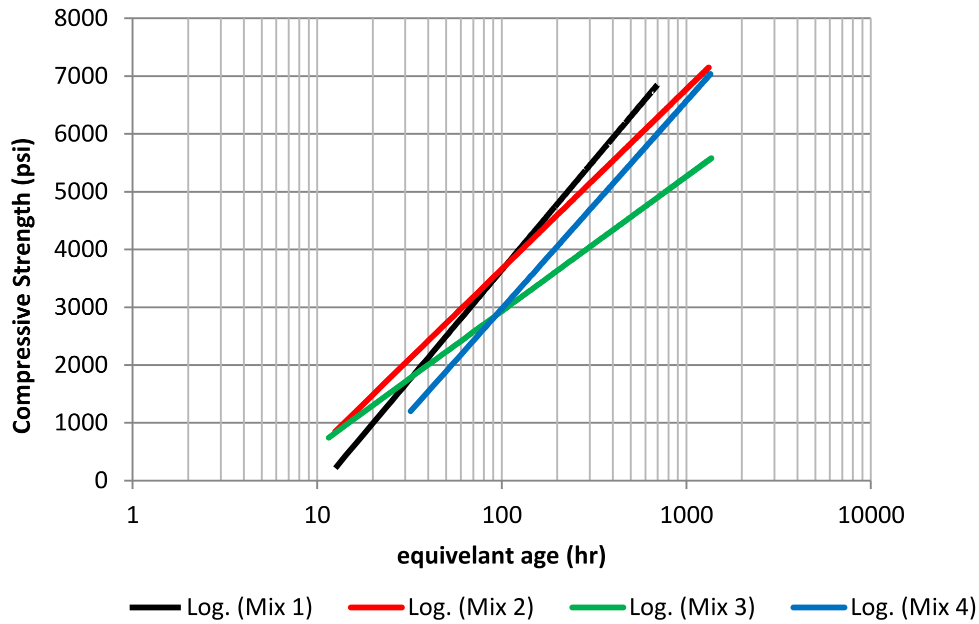


Figure 2-8: Equivalent maturity-strength curves

The constants of the Logarithm and Hansen equations are shown in Table 2-4

Table 2-4: Constants of maturity equations

MIXTURE	Logarithm equation		Hansen equation	
	a (psi)	b (psi/F/hour)	τ (hour)	β
1	-11223	3802	30	0.99
2	-7936	3087	35	0.89
3	-5899	2344	55	0.59
4	-8536	3136	50	1.36

2.4 DISCUSSION

2.4.1 Effect of materials on maturity

The concrete maturity is a map of the strength rate during the hydration process to estimate the in- place concrete strength. This rate is affected by the curing temperature. In this study we hold the curing environment fixed and observe the effect of the material proportions on maturity-strength curves. Some points were observed in this section;

• The curves follow an expected pattern.

• All mixtures subjected to the same ambience along the hydration age. Every mixture design has actually two mixtures to observe any deviation during the hydration time. The curve of maturity was almost the same as we used the exact mixture design in both mixtures and under the same curing conditions.

• Mixture (1) with the minimum cement binder (423 lbs/cy) has achieved a good compressive strength especially in later age. Development of strength rate is an indicator of the benefits of using an intermediate aggregate size in the design of the mixtures.

• Increasing cement binder in from (423 lbs/cy) in mixture (1) to (446.5 lbs/cy) in mixture (2) combined with increasing the water reducer dosage and reducing the water cement ratio; all these factors had enhanced the compressive strength comparing with the other mixtures for a certain maturity index. Mixture (2) acquired the highest compressive strength among the other mixtures as it achieved the highest compressive strength in a minimum maturity. This means that this mixture will gain the desired compressive strength faster than other mixtures.

• More increasing in cement binder from (446. lbs/cy) in mixture (2) to (493.5 lbs/cy) in mixture (3) has negatively affected on the strength gained for a certain maturity index. This can be shown clearly in Figure 2-5. Actually this mixture will require more time to achieve the desired strength compared with the other mixtures. The reason behind that belongs to the reduction in the water reducer dosage from 10.2 oz/cwt in mixture (2) to 5.2 oz /cwt in mixture (3). Also the increasing of cement binder content in mixture (3) is accompanied by reducing the amount of coarse aggregate which contribute to that strength reduction.

• The exact mixture design for mixture (3) was adopted for the following design of mixture (4), but with increasing the mid-range water reducer type DARACEM 55 from 5.2 oz./cwt. in mixture (3) to 9.2 oz./cwt. in mixture (4) has led to improvement in the strength gained for a certain maturity index. The DARACEM 55 is a lignosulphonate water reducer (WR) and a calcium nitrate accelerator. The accelerator is added to offset the retarding effect of the lignosulphonate.

2.4.2 Predicting later-age strength

Predicting later age strength by means of maturity depends on imperial equations. ASTM C918 adopted the logarithm equation in establishment the maturity-strength relation. Results obtained regarding the predicting strength was close to actual strength on the main chart of maturity-strength. The slope of the line (b) plays a big role in the value of the projected strength. The slope of the line depends on the maturity-strength relation that has been plotted according to the ASTM 1074.

2.5 CONCLUSIONS

In our study we were investigating the effect of material proportions on the maturity of concrete. The final result has shown the benefit of using a mixture design. This benefit gained in the mixtures with high strength that correspond with a low maturity index. A low maturity index for a limited strength means a short time to gain that required strength. Less time means a reduction in the cost.

In our case we got good strength with relatively low maturity in mixtures (1) and (2). These results were obtained by using a good mixture design combined by the appropriate changing in material proportions that improved the maturity-strength curve.

• Maturity of concrete is a relation that combines the temperature released during the hydration of the concrete at different times with the corresponding concrete compressive strength. This relation is unique for a certain mixture because of the variety of concrete mixture designs. The study showed the differences in concrete maturity in case we changed the proportions of the materials. Maturity of concrete is very sensitive with any change in proportions of materials even if we changed small amounts of one of the mixture ingredients.

• Maturity-strength curves can be enhanced by adding water reducer, reducing water cement ratio, and adding intermediate aggregate size.

• Predicting the concrete strength in terms of maturity has shown a close result of projected concrete compressive strength compared with the actual strength. According to ASTM C918, caution should be taken in the final result as the predicting strength of concrete in terms of early age is not adopted in design codes.

CHAPTER III

AGGREGATE GRADATION OPTIMIZATION

3.1 INTRODUCTION

It is desirable to minimize the paste content in concrete mixtures. A minimum cement paste means less cost, and protecting the environment by minimizing the emission of CO2. In addition there are benefits to minimizing concrete shrinkage, improving workability, and the concrete strength will be enhanced.

The gradation of aggregate is classified into; well or dense, uniform, gap, and open graded [25]

The one that is thought to be the most desirable is the well graded. Gradation of aggregate according to the known aggregate methods; power 0.45, haystack, Shilstone Coarseness chart can help choose the appropriate gradation [26].

Another way to think about the gradation of the aggregates is to try and minimize the voids content or maximize the density of the aggregates in a mixture. One way this is done is with dry rod unit weight of rock and sand material as per ASTM C29/C29M.

Aggregates occupy between 70 to 85% by mass of concrete or 60 to 75 % by volume for typical concrete mixtures [27]. Aggregates affect the fresh properties of concrete such as workability, and unit weight. Aggregate also affect the hardened properties like compressive stress, permeability, electric resistance and durability [27].

3.1.1 Objectives of research

The primary objective of the study is to reduce the cement content in a concrete mixture by optimizing the aggregate gradation, fly ash content, and w/cm (water to cement ratio). By reducing the cement and increasing the aggregate this will lead to reducing the costs of the mixture as the cement is often the most expensive ingredient in the mixture. This reduction in cement also helps to improve the sustainability of the mixture as cement has a large carbon footprint. The optimization of the mixture design will get the desired workability beside the main benefits like improving the strength and durability.

In this study the mixture design followed the procedures outlined by Koehler and Fowler [28].

The first step in this procedure is to choose your aggregate gradation. Next we choose the paste content so that the mixture can meet the constructability, durability, and strength needs of the in place concrete. For this work much of the effort was focused on finding mixtures with satisfactory constructability. The durability of the mixture was based on past recommendations in building codes and the strengths of the mixtures were checked in the final step. After the aggregate gradation was chosen the paste in the mixture was systematically reduced while also using a mid-range WR to change the paste viscosity. A series of paste volumes and viscosities were investigated until satisfactory performance was found.

Finally we verified the results with strength testing. It would be desirable to also investigate the durability of these mixtures. However, this was not possible with the resources on this project.

3.1.2 Aggregate properties

Fresh and hardened concrete properties are affected by aggregate properties which vary by the source. Some aggregate not suitable for concrete mixing. The properties of these properties, characteristics, and standard tests can be summarized as shown in Table 3-1

Table 3-1: aggregate properties

charachterstic	Significance of the charachterstic	Requirement
1-Shape& Texture	Affect the workability	ASTM C 295 ASTM D3398
2- Resistance to abrasion	Index of aggregate quality	ASTM C 535 ASTM C 779
3- Grading	Affect the workability of fresh concrete, mimimize the cement content	ASTM C 117 ASTM C 136
4- Bulk density (dry unit weight)	Affect the mix design calculations	ASTM C 29
5- specific gravity	Affect the mix design calculations	ASTM C 128 ASTM C 127
6- Absorption	Affect the water cement ratio	ASTM C 70 ASTM C 127 ASTM C 128 ASTM C 566
7- Compressive & flexural of Strength	Acceptability of fine aggregate failing other tests	ASTM C 39 ASTM C 78
8- Aggregate constituents	Affect the amount of deleterious and organic materials in aggregate	ASTM C 40 ASTM C 87 ASTM C 117
9- Resistance to alkali	Affect the volume change	ASTM C 227 ASTM C 289

3.1.3 Aggregate gradation

Aggregate gradation can be defined as the frequency of a distribution of the particles sizes [29].

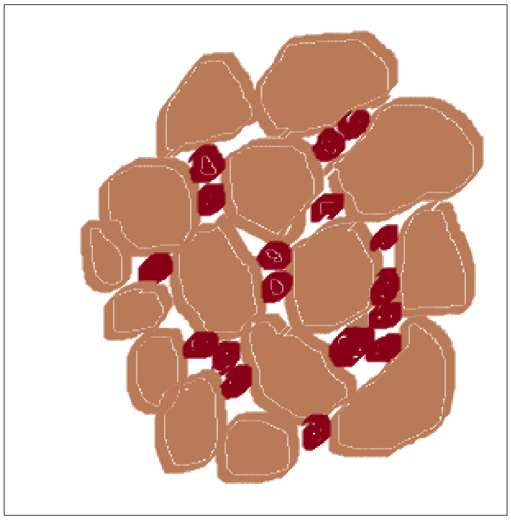
Types of gradations: Arrangement of particles with the effect of shape, textures, and angularity will lead to a certain type of gradation depends on percentage used of different aggregate sizes. FHWA classified the types of gradation as following:

1- Well graded (dense). Is the curve near line 0.45 power in which representing the maximum density line. Most HMA mix design tends to approach this line [25].The arrangement of particles as in Figure 3-1-a, which shows a grain-to-grain contact, low void content, and high density.

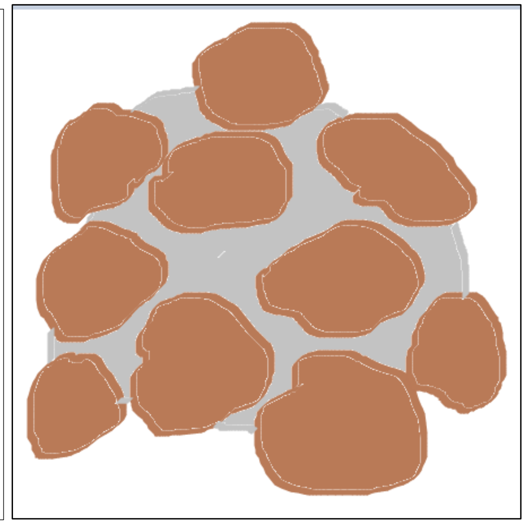
2- Gap graded. It is aggregate with a little or missing intermediate size. Using this kind of gradation will lead to segregation [25]. Figure 3-1-b is showing the particles arrangement in this kind of grade that has no grain-to-grain contact, higher void content, and lower density.

3- Open graded. It is the gradation of aggregate that contains a small amount of small particles. The blend has voids between big particles that are not filled with the missed small sizes [25]. Arrangement of this grade has grain –to-grain contact, high void content, low but variable density, as illustrated in Figure 3-1-c.

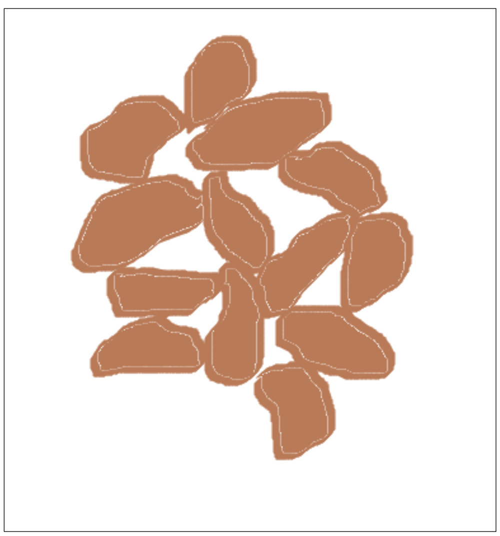
4- Uniformly graded. Most of aggregate particles are in the same size in this gradation; with steep shape [25], as in Figure 3-1-d. The arrangement in this type has grain-to-grain contact, high void content, and low but variable density.



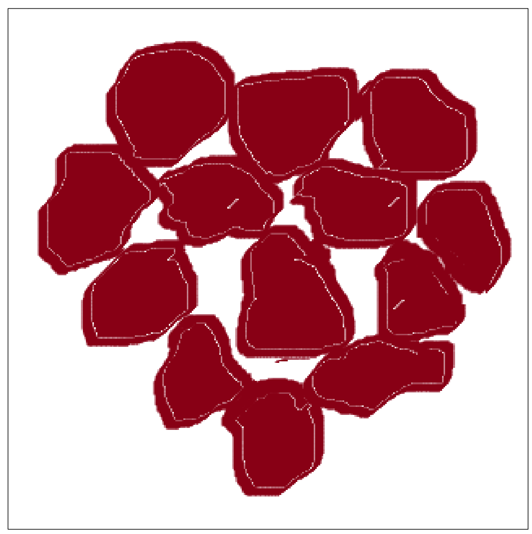
a) Well graded



b) Gap graded



c) Open graded



d) Uniform graded

Figure 3-1: Aggregate particles arrangement in different gradation curves

The idea of changing the aggregate gradation in such a way that leads to best results regarding decreasing the void ratio is not new. Many efforts started early last century to optimize the aggregate gradation in order to get less void ratio which would result in less cement or cementitious content in the concrete mixture [26]

The gradation of aggregate is affecting the properties of the concrete like strength, modulus of elasticity, shrinkage and creep [30]. There is an optimal packing of the aggregates that would theoretically require less mortar. However attention should be kept to obtain a sufficient workability.

Fine aggregate gradation is also important as it impacts the workability more than the coarse aggregate. Aggregate with fine aggregate gradation near sieve passing No 50 and 100 may suffer problems due to high surface area in workability and bleeding ASTM C 33[31]. The finer passing No 100 the bigger specific surface area that contribute to more cement paste demand [32].

Methods of optimizing aggregate gradation can be summarized as following:

3.1.3.1 Maximum density of aggregate

This method was first searched by Fuller and Thompson [33]. Later they found this curve won't necessary give the maximum density or even the maximum strength of concrete, because of the interaction between aggregate particles with water and cement is not the same as the aggregate particles packed alone. Based on this concept, Tolbot and Richart established the maximum density equation [33].

P= $(\frac{d}{D})^n$ in which (3-1)

P= amount finer than (d) size.

d= particle size.

D=Maximum particle size.

n=exponent. Governing the distribution of the particle sizes

The n value was set as 0.5 by Fuller to achieve the maximum density but this value led to harsh mixture. This value was adjusted later by Good and Lufsey in 1965 to 0.45 for asphalt mixtures [34]. Power (0.45) graph is based on Fuller packing theory. The method illustrated in various graphs and many states adopted their own chart (Figure 3-2)

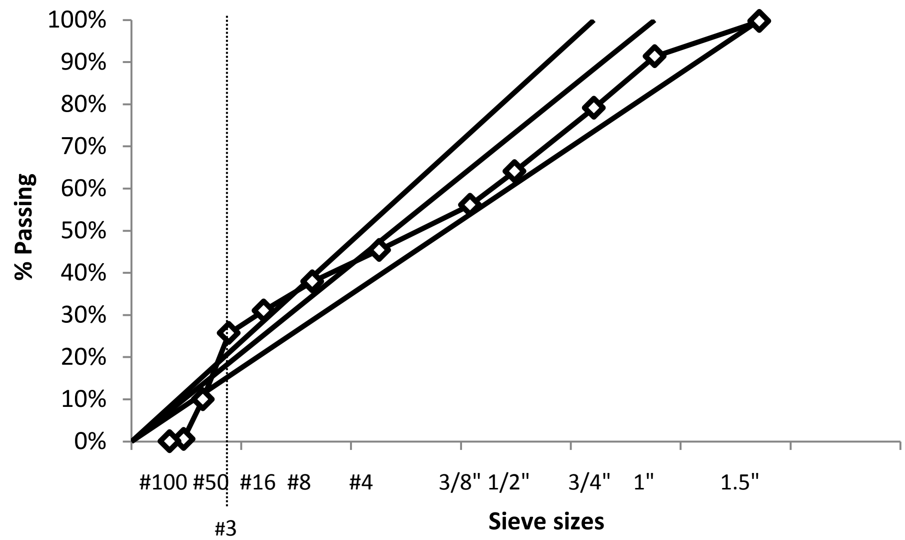


Figure 3-2: 0.45 Power line

The horizontal axis represents the sieve size raised to power 0.45, while the vertical axis represents the percent passing. Another example is adopted by FHWA, in this, the maximum density curves for 0.45 Power gradations are drawn for multiple maximum aggregate sizes. The maximum density line for each curve is drawn from the origin to its maximum aggregate size.

3.1.3.2 Fineness modulus (FM)

This method was developed by Abrams in 1918. He found that there is a relation between the aggregate gradation and the water demands. The basic idea is to reduce water content to get higher concrete strength by maximizing the fineness modulus [35] [36]:

Fineness Modulus, according to ASTM C 125, is an aggregate index computed by dividing the sum of percent retained on specified sieves over 100. Specified sieves for coarse aggregate size are; 3, 1.5, 3/4, and 3/8 in, while the specified sieves for fine size aggregate are; No. 4, 8, 16, 30, 50, and 100 which it the minimum limit. Limits of fineness modulus are typically between 2.3 and 3.1(ASTM C33). The higher value of FM, the bigger the average aggregate size. ACI 211 adopted the volumetric chart to correlate fineness modulus with basic water demand.

This method is still used today by ACI 211 for mixture design method. The method takes into account the volume of mixed particles. In the part of determining the aggregate proportions or quantities per unit volume (cubic yard), the method depends on fineness modulus of fine aggregate with respect to dry unit weight of coarse aggregate and the maximum size of coarse aggregate [35].

Table 3-2: the percent of bulk volume of coarse aggregate according to ACI 211

Nominal Max. Size (in)	Bulk Volume of Coarse Aggregate with respect to Fineness Modulus of Fine Aggregate.			
	2.4	2.6	2.8	3.0
3/8	0.5	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1.5	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

Chart of this analysis (Table 3-2), is showing as we increase the fineness modulus of a certain maximum size of coarse aggregate we will need less coarse aggregate and for a certain fineness modulus of fine aggregate we will need more coarse aggregate as we increase the maximum size of coarse aggregate.

3.1.3.3 Specific surface area of aggregate

In 1918 Edward found the specific surface area of aggregate would have an impact on the water demand of the concrete mixture. The less specific surface area, the lower the amount of water required to obtain certain workability [37]. Later in 1954 Newman and Teychenné found that if the gradation of a combined aggregate changed so that the total specific surface area changed, deferent concrete properties will in turn change. But if that change in aggregate grading kept the specific area constant, a mixture with similar properties will be produced [38].

Another method based on Newman and Teychenné and developed by Ken W. Day is assuming the particles are spheres. Specific surface area is a good method to design the mixture. But the negative side of this method is about overestimating the effect of finer particles. Ken W. Day published a modified specific surface area table in which we can correlate every sieve size by a modified number. This table is according to author experiment is overcoming the problem of overestimation of the fine particles effect on concrete workability and other properties [39].

Table 3-3: Modified specific surface area according to Day

Sieve fraction	Day modified SS values	Approx. true specific Surface (cm^2/gm.)	Surface modulus
20mm	2	1	1
20-10	4	2	2
10-4.75	8	4	4
4.75-2.36	16	8	8
2.36-1.18	27	16	16
1.18-0.6	39	35	32
0.600-0.300	58	65	64
0.300-0.150	81	128	128
<0.150	105	260	256

The above table can be used for individual aggregate size and the obtained results can be used to determine the combined specific surface area directly according to the following equation [39]:

$$SSca = [SSf \times Sand\% + SSc \times \% (1\text{-}Sand \%)] / 100 \qquad (3\text{-}2)$$

Where:

SSca = Specific Surface Area of Combined Aggregate.

SSf = Specific Surface Area of Sand (fine aggregate)

SSc = Specific Surface Area of Coarse Aggregate.

3.1.3.4 Shilstone method

The traditional methods such as fineness modulus will not give a clear indicator of effect of aggregate gradation on workability because different gradations may have the same fineness modulus. According to Shilstone the gradation of the aggregates will impact the workability of the mixture [40]. So these methods will not give a good indicator of concrete workability. Shilstone recognized this and published papers about his work in Saudi Arabia. Shilstone's ideas show that one can obtain a desired workability by changing the aggregate proportions instead of changing the water content in the mixture [41].

The Shilstone method is a volumetric based method. The main two parameters in his method are coarseness and workability factor. Coarseness factor is the percent of cumulative retained on sieve size 3/8” (9.5mm) over percent retained on sieve number 8 (2.36mm). The higher the coarseness factor, the more coarse aggregate content is in the mixture. Zones are classified into five main areas according to the mixture workability and its suitability in construction type. The Shilstone chart is shown in Figure 3-4.

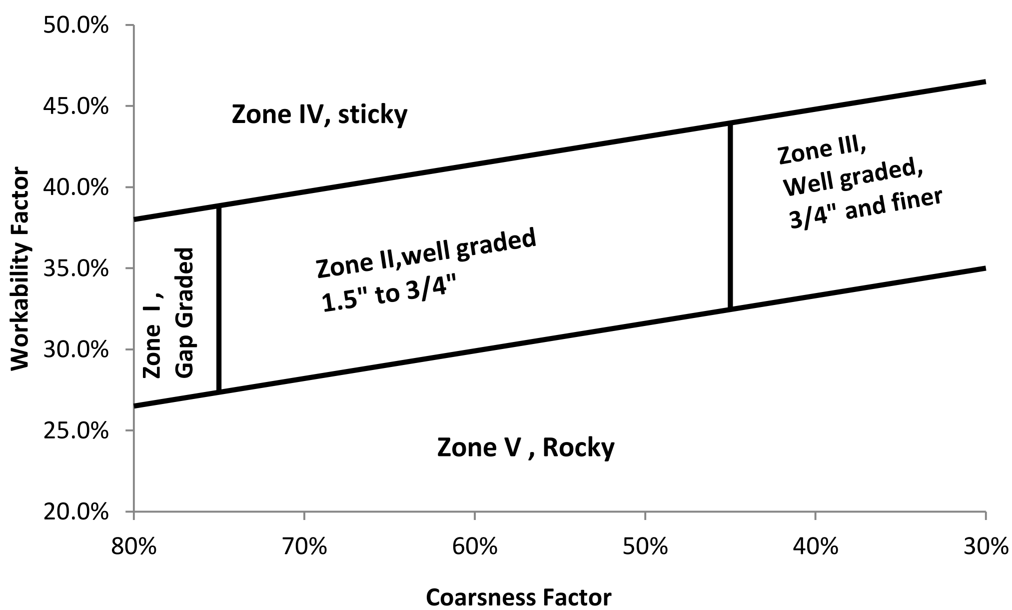


Figure 3-3: Shilstone coarseness chart

This method is currently used by many state DOTs because of its ease of use. It is also called the coarseness factor chart. Coarseness factor (which represent the horizontal axis) is computed through the equation:

$CF = Q/I * 100 \quad (\%)$ (3-3)

Where:

Q=Cumulative %retained on sieve 3/8” sieve. (Coarse size aggregate)

I=Cumulative %retained on sieve #8. (Intermediate size aggregate)

In the vertical axis we plot the workability factor values. This can be determined from the following equation:

$WF\% = W \times 2.5(C-564)/94$ (3-4)

Where:

C = Cementitious material content (lbs. /cy^3)

W=% passing #8 sieve

Coarseness factor (horizontal axis), is the percent of retaining on sieve 3/8” over retaining on sieve #8. By increasing the amount of the intermediate or fine aggregate size, the blend will be finer and the coarseness factor will decrease in value. Also, increasing the amount of coarse aggregate will increase the coarseness factor.

In the adjusted Shilstone graph, the range of coarseness factor is within 30% and 80%. Regarding the workability factor in which is a combination of binder content and passing the fine sieve # 8 would locate the point up or down on graph according to workability equation (3-4)

3.1.3.5 Percent retained, (8-18) graph

Main object of this graph is to keep gradation in a haystack shape. The percent retaining from sieve No 30 through a sieve less than the nominal maximum aggregate size should be within the range of 8% and 18% [33]. For a floor slab Holland recommended to extend the range of (8-18) to (6-22) when it is hard to find intermediate aggregate sizes [42].

8-18 charts or percent retained chart is often used to show details of the aggregate gradation, by showing in details of the percent of every percent retained for every sieve size. The main goal of this method is to limit the maximum and minimum amount of aggregate to an upper limit of 18% retained and minimum of 8% retained on sieve #30 [43]. According to this method the perfect grade would be the gradation that has grains retained by weight within the zone 8% and 18% especially for the intermediate size.

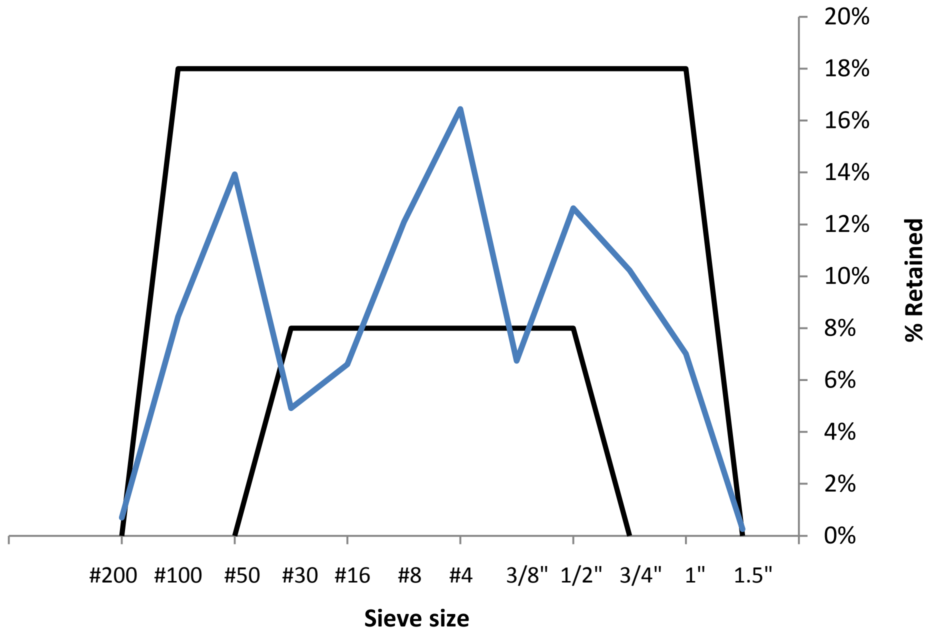


Figure 3-4: Example of (8-18) chart

3.1.4 Aggregate bulk density

3.1.4.1 Aggregate dry pot unit weight

The Voids between aggregate affect the mixture design by reducing or increasing the paste volume required to fill the cavities between the particles. Void ratio describes how tight or loose is the packing of aggregate particles. Voids increased with increasing the aggregate size. Voids ratios are also affected by the shape, angularity and texture. All these parameters are included in ASTM C29 [44] to determine the dry pot unit weight of aggregate. In this test a metal mold with known weight and volume is filled with aggregates to one third, then this layer will compacted evenly by 25 strokes from a tamping rod. A second layer will fill the two third with leveling and compacting by tamping rod without allowing the rod to penetrate to the first layer. A final layer will fill the mold to overflow and same previous procedure is applied with leveling the final surface with a plate to make the level of the compacted aggregate same as the level of the mold edge. After weighting the mold with aggregate, the dry unit weight of aggregate can be calculated according to the equation;

$$M = (G - T) / V \qquad (3\text{-}5)$$

Where:

M= bulk density of the aggregate,

G = mass of the aggregate plus the measure,

T = mass of the measure, and

V = volume of the measure.

3.1.4.2 Packing modulus

Packing is the ratio of the particles volume to the total volume or the complementary of the porosity (packing equal one minus porosity). Packing is another approach of aggregate optimization to get denser concrete with minimum amount of cementitious material which results in less shrinkage and creep with more strength and durability [45].In 1907, Fuller and Thompson studied the effect of the distribution of particles on concrete properties by changing the distribution of the packing of constituent materials within the concrete [46]. The packing theory by Furnas in 1931 stated an assumption that small particles fill out the cavities between big particles without disturbing the big particles arrangement. His Packing models have been developed based on spherical particles shape [47].

The basic packing model has been developed based on binary mixtures. The system has since been developed to multi –component mixtures [24]. The basic packing formula is:

$$\text{Packing} = Minimum_{i=1}^{n}(\alpha i + (1-\alpha i)\sum_{j=1}^{i-1} g(i,j)\text{Ø}i + \sum_{j=i+1}^{n} f(i,j)\,\text{Ø}j) \qquad (3\text{-}6)$$

Where

α is the mono disperses packing (packing for equally sized particles). This value is ranged between 0.6 and 0.64 for spherical shape particles. And be less for non-spherical shaped.

Ø is the volume fraction of a mono material.

f (I,j) is the interaction function for the wall effect and the effect of case of small particles close to larger particle size(cannot be packed dense as in bulk).

g (I,j) is the interaction function for the case when small particle are so large that cannot fit in between cavities between larger particles, without disturbing the packing of the larger particles [24].

The size for every material is divided into fractions. While the mono disperses packing is obtained by experimental lab work [49]. Mono packing will be always equals or less than the packing of the whole material. The wider distribution size within the material, the larger packing density can be obtained [49].

3.2 MATERIALS AND METHODS

3.2.1 Materials

3.2.1.1 Materials properties

All of the materials investigated were provided by Ed Bell Construction. These materials were the materials to be used on FM 1938.

Table 3-4: Materials properties and requirements

Material	Type& Source	Sp. Gr.	Requirements
1-Cement	Type l /TX.	3.1	ASTM C150 [50]
2-Flyash	Class F	2.5	ASTM C618 [51]
3-Corase Aggregate 1.5”	#57 /TX.	2.65	ASTM C127[52], ASTM C33
4-intermediate Aggregate	3/8”/ TX.	2.65	ASTM C127
5-Sand	TX.	2.65	ASTM C128[53], ASTM C33
6-Water	Tab water	1	ASTM C1602[54]
7-Water Reducer	DARACEM 55	1.28	ASTM C494[55]
8-Mid Range Water Reducer	MIRA 110	1.06	ASTM C494
9-Water Reducer	WRDA 35	1.2	ASTM C494

3.2.1.2 Concrete tests

The following tests run on fresh concrete: slump according to ASTM C143 [56], air content according to ASTM C231 [57], unit weight according to ASTM C138 [58], and the box test.

The box test is a novel test method used to determine the workability of low slump concrete. The box dimensions and shape is illustrated in Figure 3-11.

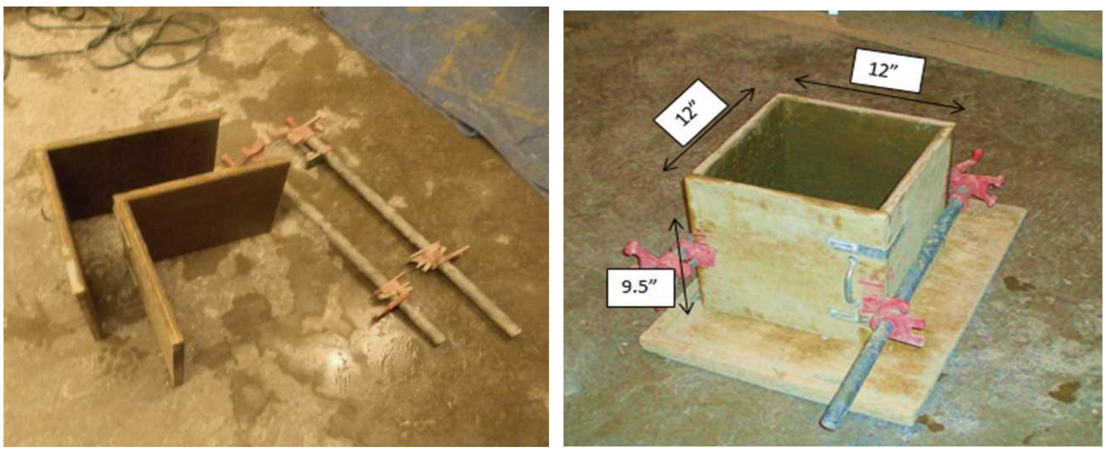


Figure 3-5: Box test; parts & dimensions

Procedure of using the Box Test:

1. Assemble the two parts of the box tightly. Using clamps as in Figure 3-5

2. The box was filled with 9.5" of unconsolidated concrete.

3. It was vibrated with a hand held vibrator for three seconds and the head is entered and three seconds as it is pulled out.

4. Untighten the two parts of the box and separate them gently.

5. If the obtained shape has a good straight edge with good top and only minor unfilled voids then the test has been deemed to pass. If the shape has a slumped edge or significant voids on either the sides or the top, the sample is considered to fail the test.

a) Pass b) Fail

Figure 3-6: Box test conditions

Concrete compressive strength was also measured according to ASTM C39 [59] on hardened concrete samples for ages 7 and 28 days.

3.2.2 Methods

3.2.2.1 Aggregate optimization

The basic start to optimize gradation is by combining two or three aggregates with different proportions then investigate these proportions according to gradation methods associated with packing density of these combined aggregate. Obtained results will be used in pavement mixture design.

3.2.2.1.1 Sieve analysis & combined aggregate gradation

We completed the sieve analysis for the individual aggregate sizes as per ASTM C136 [60].

We did the following Steps:

1- We selected suitable sieve sizes according to the aggregate sizes

Table 3-5: Aggregates Sieve Sizes

G3	3/8"	Sand
Sieve Number	Sieve Number	Sieve Number
1.5"	1/2"	#4
1"	3/8"	#8
3/4"	No. 4	#16
1/2"	#8	#30
3/8"	#16	#50
No. 4	#30	#100
Pan	#50	Pan
	#100	
	Pan	

1- Thoroughly sieve the aggregates

2- Weight every sieve with the retained particles, and then subtract sieve weight from the obtained result to get the retaining weight for aggregate particles on every individual sieve size.

3- Percent passing can be determined by subtracting the cumulative weight on every sieve from 100%.

After we determined the sieve analyses for the individual aggregate sizes, we compute the combined aggregate gradation according to ASTM C136 specifications for chosen gradations according to the following equation:

$$P = Aa + Bb + Cc \quad (3\text{-}7)$$

Where:

P = Combined percent passing of a given sieve

A, B, C = Percent passing for aggregate A, B, and C for each sieve.

a, b, c = Relative percent of total aggregates A, B, and C.

The combined aggregate gradation will be used in the gradation methods.

3.2.2.1.2 Aggregate gradation by power.45

The maximum nominal aggregate size is the one sieve size larger than the sieve that has less than 90% passing. In our case this size is 1”, as the first top sieve less than 90%passing is sieve ¾”. The nominal proportions of aggregate blends were investigated according to power 0.45 to choose gradations close to the max density line. This is the first step towards optimizing the gradation. Next the mixtures were varied systematically by 150 lbs. of each aggregate while holding the percentages of the other materials constant and the values were observed. This was done to investigate the sensitivity of the values in the different aggregate gradation techniques. These are plotted in each of the graphs below.

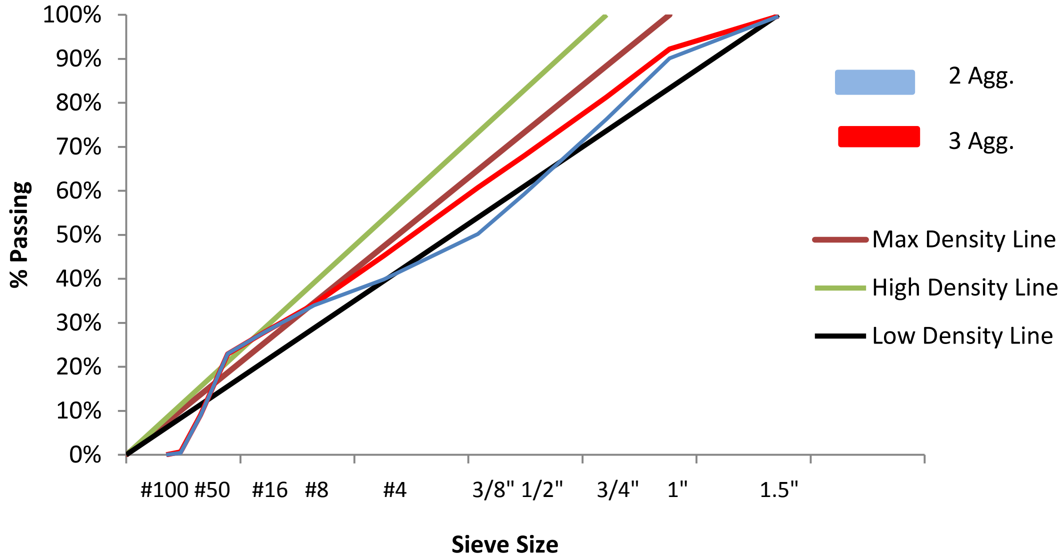


Figure 3-7: Three and two aggregate blends plotted in power (0.45) chart

3.2.1.1.3 Percent retained (haystack shape) charts

The gradations of aggregate blends either (G3, 3/8", Sand) group or (G3, Sand) group will be verified in percent retained chart to identify gaps in the gradation as shown in Figure 3-8

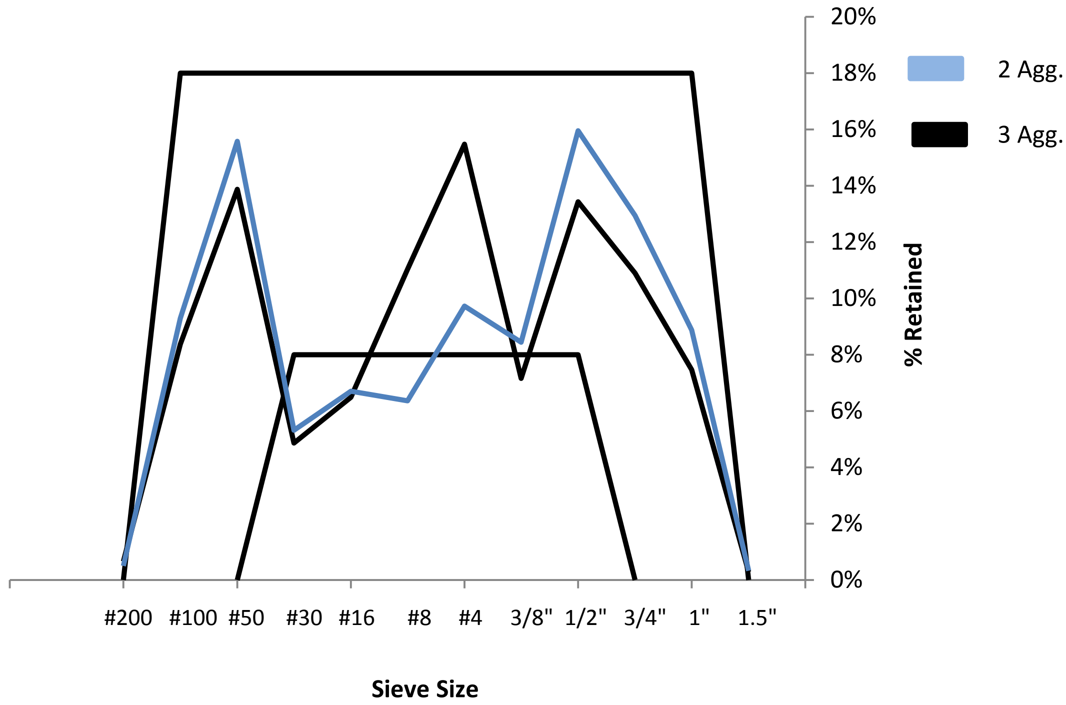


Figure 3-8: Percent retained chart for three and two aggregate blends

3.2.1.1.4 Shilstone method

In this method a number of gradations were plotted in Shilstone chart while holding the cement binder fixed to observe the effect of the gradation. Figure 3-9 is illustrating this case for the two groups of aggregate blends with the associated aggregate void ratio as determined by ASTM C29.

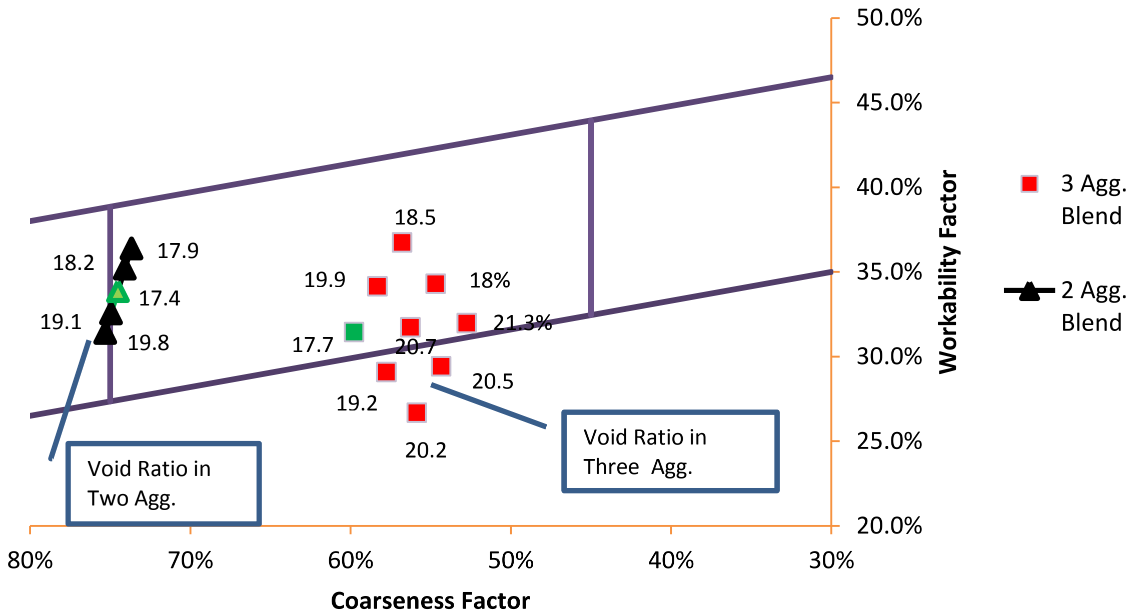


Figure 3-9: Aggregate void ratio in Shilstone chart

3.2.1.1.5 Aggregate dry pot unit weight &void ratio

This technique used the coarse and fine aggregates in different ratios to find the one that had the highest dry unit weight or lowest voids content according to ASTM C29. This technique is useful as it helps the user to take into account the size, shape, and angularity of the different aggregates. We determined the aggregate void ratio according to ASTM C29, as following:

$M = (G - T) / V$ (3-8)

$\%Voids = 100*(S \times W) - M/(S \times W)$ (ASTM C29) [3].

Where:

M = bulk density of the aggregate, kg/m3 [lbs. /ft^3],

G = mass of the aggregate plus the measure, kg [lb.],

T = mass of the measure, kg [lb.],

V = volume of the measure, m3 [ft^3], and

W=density of water, 998 kg/m3 [62.3 lbs. /ft^3].

S = bulk specific gravity

The dry unit weight is calculated for multiple aggregate gradations to show the general trend of the unit weights of aggregates when we change the percentage of the aggregates.

3.2.2.2 Mixture design

The main goal is to reduce the cement content and get a good concrete workability with adequate strength.

The mixture design is based on the obtained results of aggregate gradations in the previous steps.

For a selected aggregate gradation a volume of paste, w/cm was chosen. Concrete was produced with these materials and properties like workability, the impact of the vibrator on the mixture, air content, and strength were examined. If satisfactory results were found for the mixture then the paste volume was decreased and the mixture was investigated again. At this point lower paste volumes were used with WRs to change the viscosity of the mixture until they were found to pass.

This process was repeated until we found a concrete mixture with satisfactory performance and minimized paste volume.

3.3 RESULTS

3.3.1 Aggregate optimization

3.3.1.1 Sieve analysis

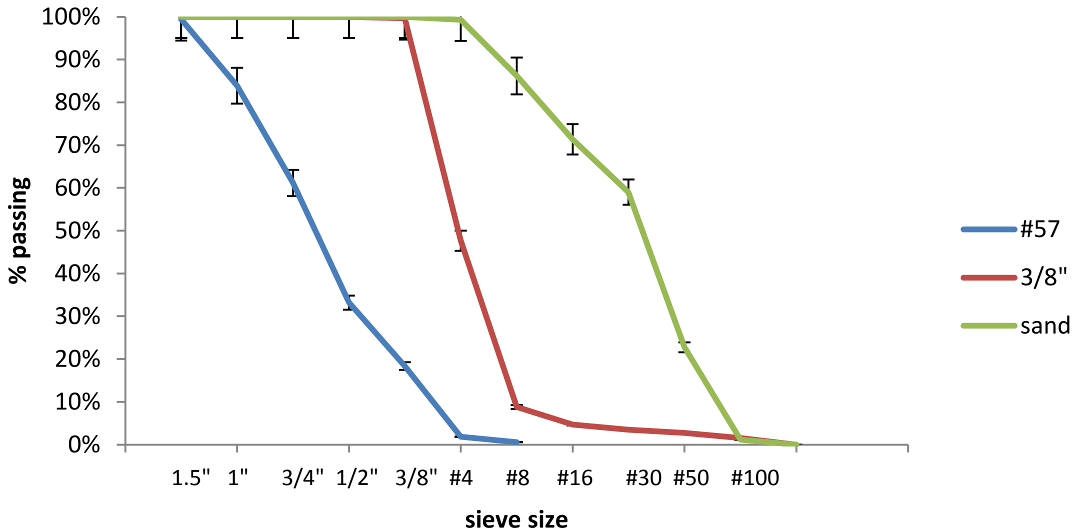


Figure 3-10: Individual Texas aggregate gradation

3.3.1.2 Power 0.45

In Power 0.45 method; the following gradations achieved the best results in approaching the dense line in three and two aggregate blends respectively:

Table 3-6: best gradation in power .45

G3	3/8”	Sand
48%	14%	38%
58%	0%	42%

Figure 3-11; is showing the two gradations on power (0.45) chart

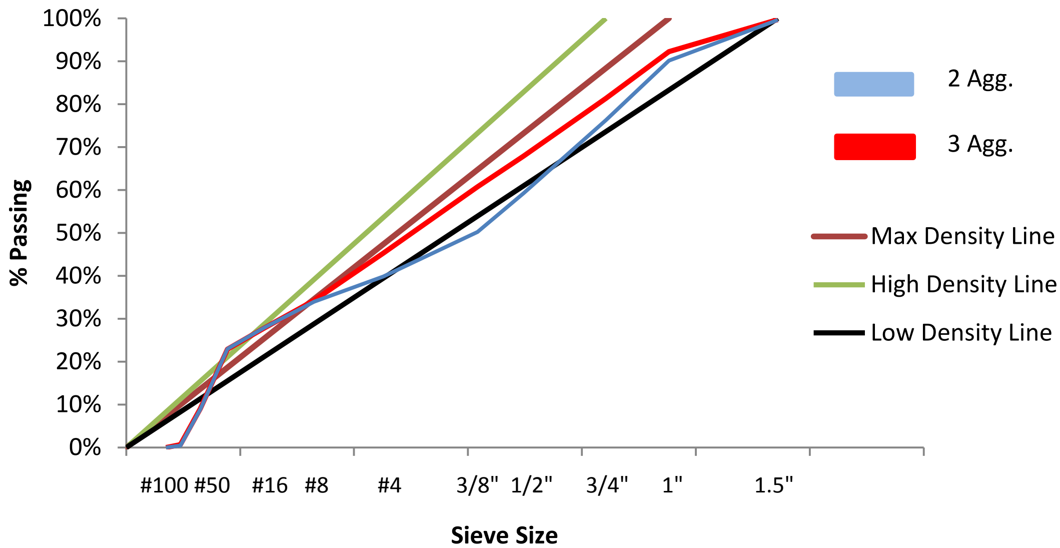


Figure 3-11 Good aggregate gradations for three & two aggregate blends

3.3.1.3 Percent retained graph

The three aggregate gradations had shown acceptable result in percent retained graph with two separated valleys (one of them is small valley shape). The two aggregate gradations have two consecutive valleys.

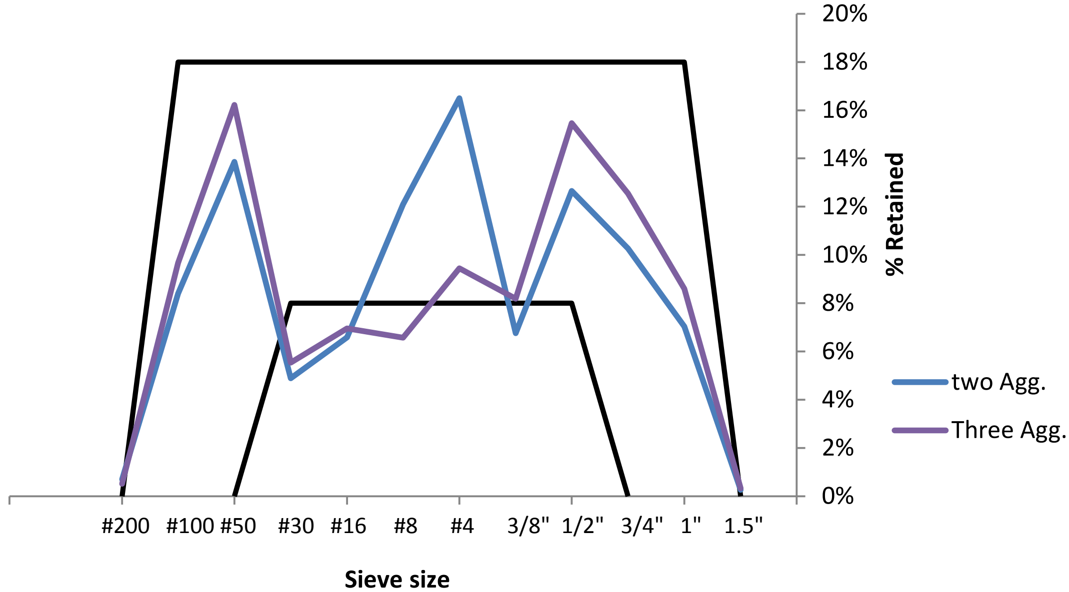


Figure 3-12: Good gradations of three and two aggregate blends in (8-18) chart

3.3.1.4 Shilstone chart

The following figure is showing the mixtures 10 and 18 in Shilstone chart.

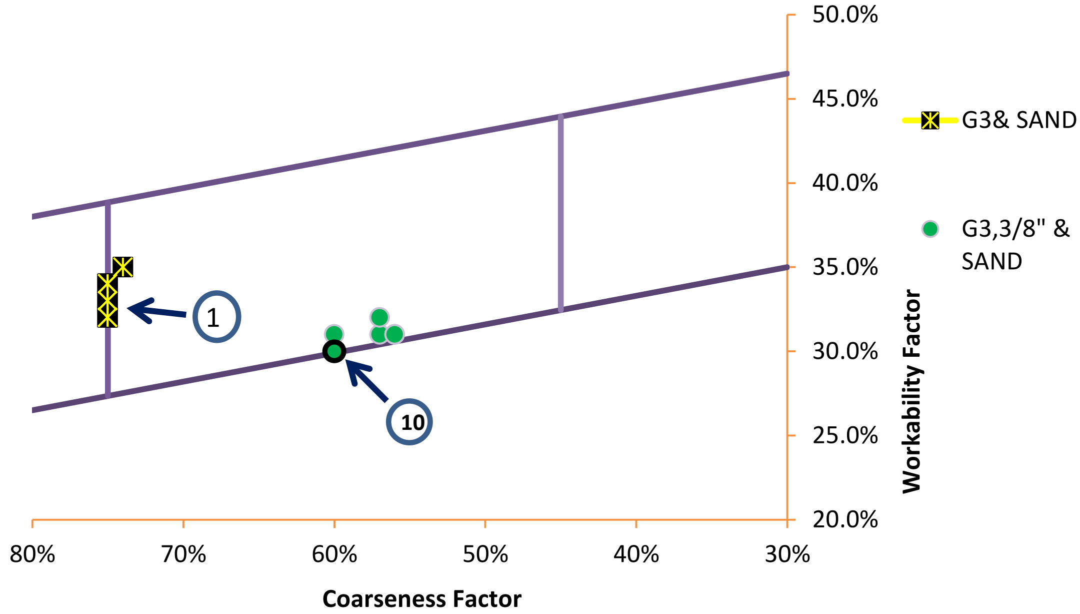


Figure 3-13: Mixtures 10 and 18 plotted on Shilstone chart

3.3.1.5 Aggregate dry unit weight

The aggregate dry pot unit weight and void ratio results are as per ASTM C29 are listed in Table 3-7.

Table 3-7: Aggregate dry unit weight& aggregate void ratio

Blend No.	Aggregate type & Size	Aggregate Percentage			Unit Weight (b/ft^3)	Void Ratio %
		G3	3/8"	Sand		
1	Grade 3	100%	0%	0%	100.85	39.0
2	3/8"	0%	100%	0%	106.00	35.9
3	Sand	0%	0%	100%	111.76	32.4
4	Grade 3 & 3/8"	88%	12%	0%	104.04	37.1
5	Grade 3 & 3/8"	86%	14%	0%	106.61	35.5
6	Grade 3 & 3/8"	81%	19%	0%	105.45	36.2
7	Grade 3 & 3/8"	76%	24%	0%	108.00	34.7
8	Grade 3 & 3/8"	75%	25%	0%	108.67	34.3
9	Grade 3 & 3/8"	74%	26%	0%	107.20	35.2
10	Grade 3 & 3/8"	72%	28%	0%	109.07	34.0
11	Grade 3 & 3/8"	70%	30%	0%	108.96	34.1
12	Grade 3 & 3/8"	68%	32%	0%	110.45	33.2
13	Grade 3 & 3/8"	67%	33%	0%	110.45	33.2
14	Grade 3 & 3/8"	66%	34%	0%	106.39	35.7
15	Grade 3 & 3/8"	65%	35%	0%	110.53	33.2
16	Grade 3 & 3/8"	64%	36%	0%	108.93	34.1
17	Grade 3 & 3/8"	62%	38%	0%	108.32	34.5
18	Grade 3 & 3/8"	57%	43%	0%	109.60	33.7
19	Grade 3 & 3/8"	52%	48%	0%	109.36	33.9
20	Grade 3 & 3/8"	48%	52%	0%	111.68	32.5
21	Grade 3, 3/8"/sand	48%	17%	35%	133.65	19.2
22	Grade 3, 3/8"/sand	48%	20%	31%	132.03	20.2
23	Grade 3, 3/8"/sand	48%	14%	38%	136.08	17.7
24	Grade 3, 3/8"/sand	45%	17%	38%	131.09	20.7
25	Grade 3, 3/8"/sand	45%	20%	35%	131.49	20.5
26	Grade 3, 3/8"/sand	45%	14%	41%	132.48	19.9
27	Grade 3, 3/8"/sand	42%	20%	38%	130.16	21.3
28	Grade 3, 3/8"/sand	42%	17%	41%	135.63	18.0
29	Grade 3, 3/8"/sand	42%	14%	44%	134.69	18.5
30	Grade 3, 3/8"/sand	46%	16%	38%	133.00	20.1
31	Grade 3/sand	61%	0%	39%	132.60	20.0
32	Grade 3/sand	60%	0%	40%	134.60	20.3
33	Grade 3/sand	58%	0%	42%	136.67	17.4
34	Grade 3/sand	57%	0%	43%	135.23	18.2
35	Grade 3/sand	55%	0%	45%	135.76	17.9
36	Grade 3/sand	59%	0%	41%	135.00	20.4

3.3.2 Mixture design

Table 3-8: Mixtures Designs and tests results

Mix #	binder (sacks)	fly ash %	Percentage of aggregate			w/c	Add Mixture		Dry U.W. (b/ft^3)	Slump (in)	Box Test	Concrete unit Wt. (b/ft^3)	AIR%	comp. (psi)	
			G3	3/8"	Sand		TYPE	oz/cwt						7 day	28 day
1	4.73	35%	46%	16%	38%	0.41	Daracem 55	11.9	133.0	0.25	Pass	148.6	2%	5239	6974
2	5	35%	45%	17%	38%	0.41	Daracem 55	4.5	131.1	0	Pass	148.8	5%	4711	6560
3	5	35%	45%	17%	38%	0.41	WRDA 35	6.2	131.1	0.5	Pass	147.2	5.5%	4187	5964
4	5	35%	45%	17%	38%	0.41	WRDA 35	5.1	131.1	0.25	Pass	147.4	5%	4058	6021
5	4.75	35%	45%	17%	38%	0.43	Daracem 55	1.9	131.1	.5"	Fail	149.7	4.1%	4507	6378
6	4.75	35%	45%	17%	38%	0.45	Daracem 55	6.3	131.1	1.5"	Pass	148.8	4.6%	4152	5473
7	4.75	35%	45%	17%	38%	0.45	Daracem 55	6.3	131.1	1.5"	Pass	149.4	1.5%	5066	7554
8	4.75	35%	45%	17%	38%	0.45	MIRA 110	5.6	131.1	1"	Pass	148.4	4.2%	3248	4928
9	4.73	35%	48%	14%	38%	0.45	MIRA 110	4.0	136.1	1.25"	Pass	149	3.9%	3235	5052
10	4.5	35%	48%	14%	38%	0.45	Daracem 55	6.0	136.1	.75"	Pass	148.5	4.4%	3624	5299
11	4.25	35%	48%	14%	38%	0.45	Daracem 55	10.4	136.1	.5"	Fail	150.1	4.3%	4743	5785
12	5	35%	57%	0%	43%	0.41	Daracem 55	7.5	135.2	0.25	Fail	148.4	5.0%	4814	7228
13	5.5	35%	59%	0%	41%	0.41	Daracem 55	4.5	135.0	1	Fail	148.2	5%	4797	6553
14	4.7	31%	60%	0%	40%	0.45	Daracem 55	3.3	134.6	4.5	Pass	148.3	4.8%	3240	4553
15	5.2	30%	61%	0%	39%	0.45	Daracem 55	3.2	132.6	7.25	Fail	143.4	7.5%	4369	5871
16	5	35%	58%	0%	42%	0.43	Daracem 55	7.7	136.7	1"	Pass	148.2	4.5%	4157	6131
17	4.75	35%	58%	0%	42%	0.43	Daracem 55	10.0	136.7	3/4"	Pass	148.1	4.8%	4279	6083
18	4.5	35%	58%	0%	42%	0.43	Daracem 55	13.3	136.7	1.5	Pass	142.3	8.6%	3902	5627

3.4 DISCUSSION

3.4.1 Gradation methods

1- The power .45; using this method is showing how the gradation curves close or far from the maximum density line. In our case the gradation curves of the three aggregate blends were (between the maximum and low density line). This is an indicator that these blends are dense with bias to be rocky.

Same results were obtained for the two aggregate blends with tendency to the rocky zone from sieve #4 to sieve size 1.5", and lean towards the sandy zone from sieve #100 to #4. The curve shapes are showing a good approach to the maximum density line in general.

2- Percent Retained (8-18%); the result is showing two separate valleys in the three aggregate blends, one of them is very small and can be ignored while the big one is under sieve #50 indicating a lack in that aggregate size in that aggregate blend. Under the chart roles, this blend is acceptable.

The curve of the two aggregate blends is showing two consecutive valleys under sieves #50 and #16. The valleys denote to the lack of aggregate size of #50 and 16 respectively. Under the roles of this chart the curve may considered unacceptable because of the consecutive valleys. But the final results of the mixture properties may break the roles.

3- Shilstone Coarseness Chart. We can see the effect of aggregate gradation on Shilstone chart as we hold the cement binder fixed (470 lb.) and varied the aggregate gradation in a consistent way. The best way to show the gradation is by plotting the void ratio associated with every gradation along on the chart. The void ratios for the three aggregate blends were varied. The minimum void ratio (17.7%) was lying in the well grade zone, close to rocky zone as a result of using the gradation (48%G3, 14% 3/8", 38% Sand) in which we can observe the highest percentage of coarse aggregate comparing with other three gradation blends, this percentage affected the value of the coarseness factor in Shilstone chart and shifted the point to the left of the points group.

In the mixture design we insert the real value of the cement binder in Shilstone equation, and the effect of the cement binder was clear on the three aggregate blends as most points were shifted down towards the rocky zone but they still in the well graded zone.

The points of the two aggregate blends were not affected a lot but we can see an inclination towards the gap zone as we decreased the cement binder and increase the aggregate content.

3.4.2 Aggregate packing density

Higher results of aggregate dry unit weight have been obtained from blends of G3 with sand and from blends of G3, 3/8", and sand. The gradations of aggregate that had been obtained by the aggregate methods had shown highest values of the associated dry unit weight. The good particle distribution had led to a good packing of the aggregate particles with a minimum void ratio.

3.4.3 Mixture designs

We used the optimized gradations that we already got and varied the paste volume. We started with a certain amount of cement binder and check the obtained fresh concrete properties like workability, air content, and response to the vibrator. We increased the cement binder as we got harsh cement with low slump in first mixture.

Enhancing the workability for a certain mixture was done by increasing the dosage of the water reducer.

In following steps; reducing of the cement binder was associated with increasing of the aggregate amount in the mixture for a certain aggregate percentage. The workability and the mixture viscosity were observed. The viscosity of the mixture observed by the Box test that gives us an indicator of the mixture response to vibrator.

More reduction in cement binder was combined by switching to aggregate gradation with high aggregate packing with minimum void ratio. This also was combined by increasing the water-cement ratio a bit. Increasing the water-cement ratio with a suitable amount of Mid-Range Water Reducer was necessary to provide a mixture neither harsh nor sticky.

3.5 CONCLUSIONS

Reducing the cement binder was the subject of many studies. This research used an optimization of the aggregate gradation to achieve this goal. Gradation curves varied according to particle distribution and packing. The particle distributions were improved by using the gradation methods while the particle packing is verified according to the packing density methods.

- Power .45 was a good gradation tool for the aggregates and other materials investigated.

- Percent Retained Chart. We got valleys in two aggregate blends but it works in our mixture and achieved good concrete properties.

- Shilstone coarseness chart; for mixtures with three aggregate blends the points were lying in the well graded zone and close the rocky zone. While the points of mixtures with two aggregate blends were also lying in the well graded zone but close to the gap graded zone.

• Dry rod unit weight of aggregate is a useful method to estimate the void in a bulk volume of aggregate. There are assumptions made in gradation charts that can be directly measured with the dry rod technique.

• Using the optimized gradations with choosing the appropriate cement content, water cement ratio, chemical admixture has led to good mixture design that reduced the amount of cement binder, acquired good compressive strength, with a suitable workability for pavement works. Verification of the mixture response to the vibrator has been successfully done by the Box test as it shows the workability and the viscosity of the concrete at the same time.

• Good results in this chapter were achieved by using 4.5 sacks of cement binder with the aggregate gradation that have a minimum void ratio:

(48% G3, 14% of 3/8”, and 38%Sand) and

(58% G3 and 42% Sand)

CHAPTER IV

CONCLUSIONS

A reduction in cement binder in a concrete mixture that provides good concrete properties was the target in this study. The two main concrete properties that we investigated were the strength and workability.

In chapter II (Concrete Maturity) we investigated the effect of concrete ingredients on the gained strength in terms of concrete maturity. In this regard we obtained different maturity-strength relation as we changed the proportions of the same materials under the same ambient conditions. In the same chapter we obtained a close result of the predicted strength to the actual strength by using the logarithm equation.

In chapter III (optimization aggregate gradation) we investigated the mixture designs so we can get a desired workability for a pavement construction. The benefits of optimizing the gradations were noticeable as we achieved a good reduction in cement paste required to fill the aggregate voids.

Optimization the aggregate gradation is not enough to attain a good mixture. Selecting the appropriate type and dosage of water reducer with a suitable water-cement ratio that provides the desired workability and strength is also important in achieving a satisfactory concrete with reductions in cement binder.

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Scope and Method of Study:
The goal of this study is to provide a mixture design that needs a minimum amount of cement content for pavement concrete. The reduction in cement content was achieved by using different aggregate gradations. Maturity curves were developed for the final design mixtures as inputs for computer models that describe the long term performance of the materials. This work was funded by a grant from the FHWA for the Highways for Life Program. The mixture developed has been used on FM 1938 near Ft. Worth, TX with satisfactory performance.

Findings and Conclusions:
- changing the proportions of the same materials under the same ambient conditions led to a different maturity-strength relation.
- The predicting of concrete strength in terms of maturity logarithm equation was close from the actual strength.
- Optimization the aggregate gradation should combined by selecting the appropriate type and dosage of water reducer with a suitable water-cement ratio that provides the desired workability and strength.

ADVISER'S APPROVAL: Tyler Ley