CAIT-UTC-REG60

Low-Carbon Concrete Pilot Program

Aggregate Optimization Strategies for LCCP Program

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16. Abstract

The optimization of the aggregate gradation and packing degree in concrete can contribute reduction in the amount of cement without loss of mechanical properties, which leads to development of concrete with significantly less carbon footprint from cement consumption. This study presents several criteria to optimize the binary and ternary blends of aggregates of different sources and gradations. The optimization is based on aggregate particle size distribution (PSD), aggregates packing degree (PD), and aggregate workability factor and coarseness factors. The experimental and multiple theoretical methods have been employed to identify the aggregate blends of the highest PD. These aggregate blends are further optimized by utilizing the gradation techniques with power curves (PC) and coarseness charts (also known as Shilstone charts). The study demonstrated agreement between the theoretical PD obtained from the Modified Toufar model and the experimental PD obtained from aggregate blends. Finally, the Shilstone chart presented the workability and coarseness factors of different aggregate blends considering various cement contents. Additional work on the determination of strength and global warming potential (GWP) of the concrete mix with the optimized aggregate blends must be performed to achieve a conclusive understanding of the correlation between the aggregate optimization with the reduction in cement consumption and sustainability of concrete. The aggregate optimization strategies in this study are being implemented into a broader scheme to reduce carbon footprint of concrete using supplementary cementitious materials among other approaches.

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DESCRIPTION OF PROBLEM

Concrete production attributes 8-9% of anthropogenic CO_2 emissions and 2-3% of annual energy demand, globally [1-4]. Even though the greenhouse gas (GHG) emissions associated with unit kilogram production of concrete are lower than that of steel, glass, and several polymers [5], the overall emissions resulting from concrete production are huge due to the global scale on which concrete is produced. Concrete is the second-most consumed material in the world with an annual production of over 3.8 tons per person [6] owing to its considerably low cost, high compressive strength and durability, universal accessibility of constituent materials, and ability to cast into any size or shape. Traditional concrete is composed of ordinary portland cement, coarse aggregates, fine aggregates, and water. Among all the constituents of concrete, cement production, which involves the combustion of fuels and calcination of limestone, is the major contributor to CO_2 emissions by contributing at least 70% of the total emissions of traditional concrete [7]. Therefore, reduction in cement content is a keyway to minimize the cement consumption and the overall carbon footprint associated with concrete production worldwide. The challenge is in reducing the cement content without sacrificing the mechanical properties or facing practical challenges in placement of such low-cement-content concrete.

APPROACH

Over the last decade, several strategies to mitigate the CO_2 footprint associated with concrete production have been developed. Material substitution using by-products and low-carbon inorganic binders and minerals [8-10], carbon capture and storage (CCS) [11-12], aggregate packing degree optimization [13-15], and alternative fuel and efficient technology for the combustion of clinker [16-17] are a few of the approaches considered to produce sustainable concrete. The most common approach for reducing concrete-related emissions is substituting cement with supplementary cementitious materials (SCMs) which are generally obtained as the by-product of other industries. The most common SCMs includes fly ash, ground granulated blast furnace slag (GGBFS), and silica fume which are the by-product of coal-based power plants, steel plants, and/or ferrosilicon alloy industry, respectively [18]. Moreover, several studies have shown that SCMs enhance the mechanical performance and durability of concrete through cementitious or pozzolanic reactions [19-20]. Figure 1 shows the reduction of CO_2 emissions per unit weight by 25-37% by replacing 25-50% of cement with different SCMs [21].

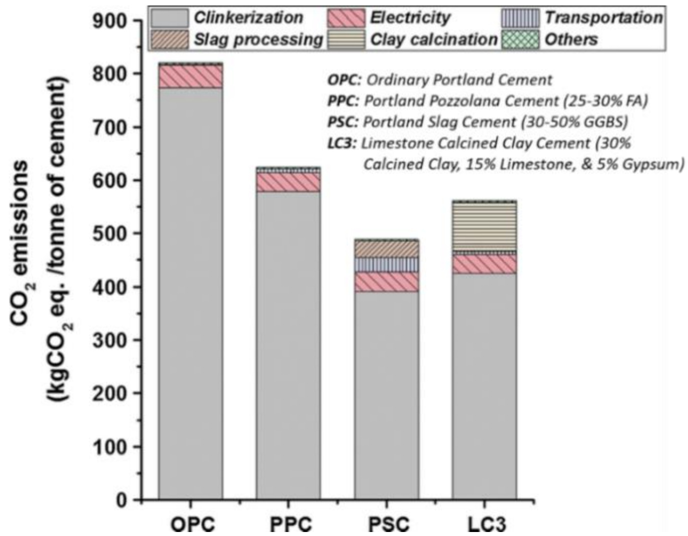

Figure 1. Comparison of CO_2 emissions of ordinary portland cement with different SCMs substituted cement [21]

The optimization the aggregates packing degree (PD) and gradation is an efficient approach to reduce the cement content in concrete, complementary to the use supplementary cementitious materials, while preserving or improving the mechanical performance of concrete. The aggregate PD has been optimized experimentally by researchers using Vibro-compacting aggregates of different sizes in various proportions [15, 22-23]. Analytically, several studies have implemented various theoretical particle packing models, such as the Toufar model [15,24], modified Toufar model [25], Furnas model [26], Dewar model [27], Aim model [23], and compressible packing model [28] to optimize the aggregate PD. Some studies have developed computational simulation models to optimize aggregate packing using algorithms like the sequential packing model [29] and Random Sequential Addition (RSA) model [30].

Other studies have showed that compressive strength increases with the PD while maintaining the amount of cement, however, the correlation between strength and PD may range from weak to strong depending on the w/c ratio and presence of supplementary material in concrete [15, 31-32]. For instance, a study has shown that the optimization of PD can increase compressive strength by up to 156% in concrete composed of recycled aggregates [32]. In a separate study, an improvement of up to 37% in compressive strength has been observed following the aggregate packing optimization in traditional concrete for the same amount of cement [15].

The objective of this study is to optimize the aggregate blends based on multiple criteria such as experimental and theoretical packing, grading techniques based on power curves (PC), and the Shilstone chart. The optimized aggregate blends obtained from several criteria are compared and the best blend in terms of packing degree, gradation, and coarseness factor is obtained for combinations of aggregates from various sources. In principle, the goal of optimizing aggregate packing is to reduce the amount of cement while maintaining the compressive strength and durability performance all while ensuring adequate concrete workability for practical implications. Furthermore, the findings of this study can be used for determining the optimal concrete mixtures with suitable mechanical properties while considering the global warming potential (GWP); The results of which provide insight about concrete with optimized aggregate blends and the correlation between aggregate packing, strength, and GWP (Fig. 2).

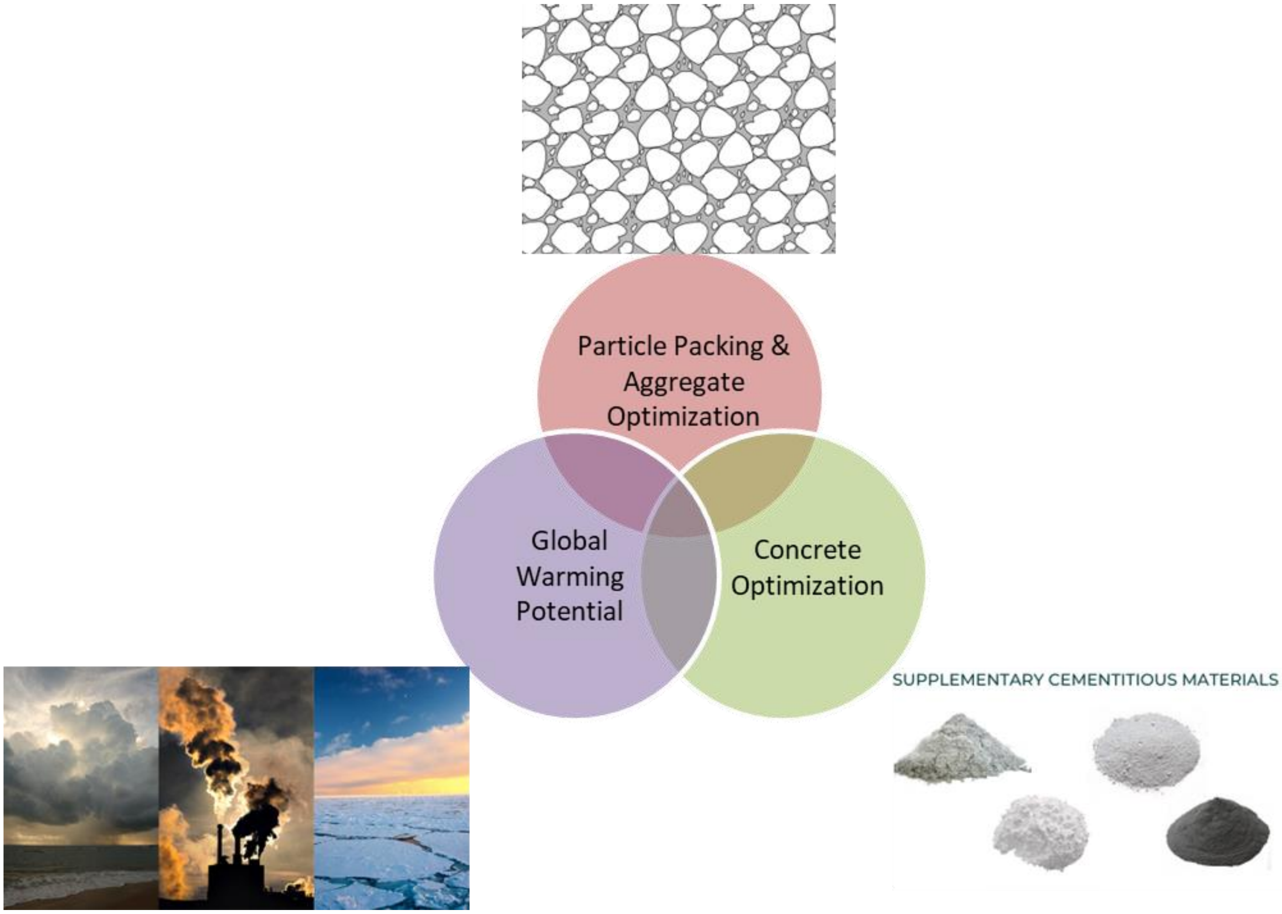

Figure 2. GWP of concrete by optimizing aggregate packing degree and incorporation of SCMs

METHODOLOGY

Aggregate Gradation

The type and properties of different types of aggregates used in this study are summarized in Table 1. The particle size distribution of aggregates (Figure 3) was determined by the sieve analysis according to ASTM C33 [33].

Table 1: Properties of individual aggregate

Aggregate	Type	Specific Gravity	Percent Absorption (%)	Bulk Density (lb/yd^3)	
				Loose	Compacted
Hamburg Coarse	#57 stone	2.62	-	2098	2538
Weldon Coarse	#57 stone	2.85	-	2218	2619
Wantage Intermediate	#8 stone	2.80	1.7	2279	2667
Weldon Intermediate	#8 stone	2.72	-	2231	2638
Clayton Fine	Natural Sand	2.63	0.6	2715	3159

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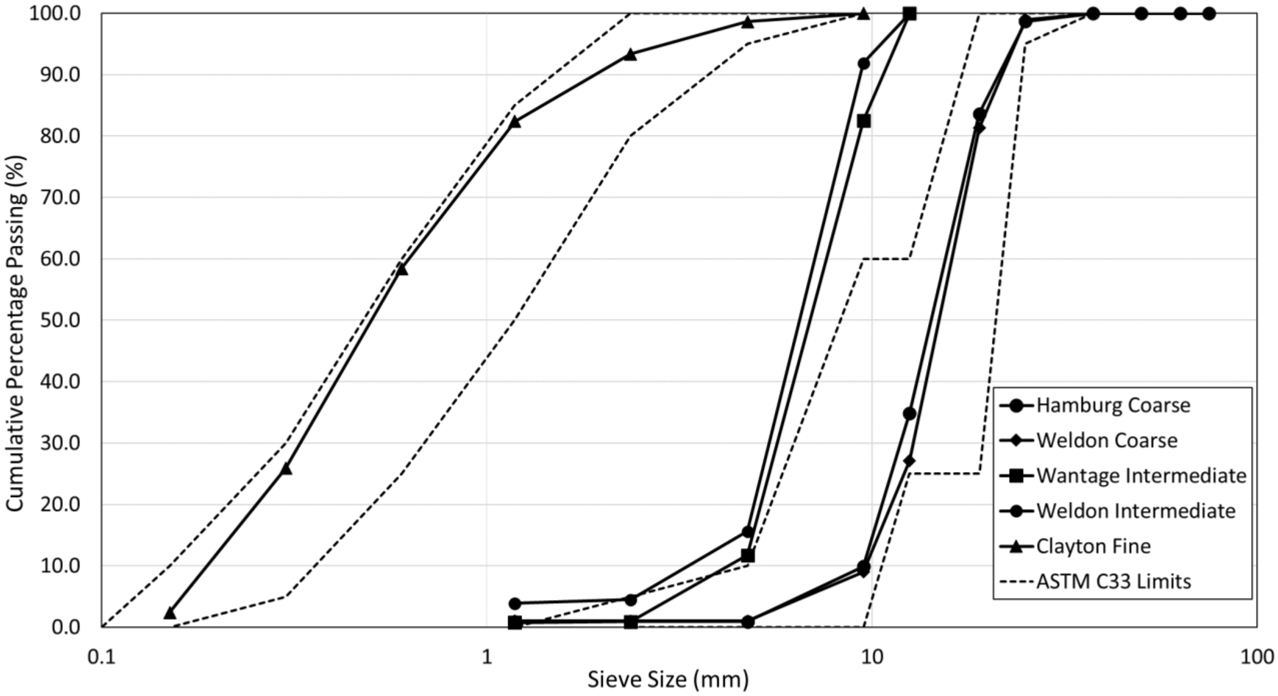

Figure 3. Sieve analysis of individual aggregate

Experimental Evaluation of Packing Degree

The VB apparatus was initially developed for zero-slump concrete and is currently used to measure the consistency and density of roller-compacted concrete. In this study, the packing degree of different aggregate combinations was evaluated using the VB Vibro-compacting apparatus (ASTM C1170, method A) presented in Fig. 4. The aggregate blends were selected based on different volume proportions of individual aggregates. The total weight of the aggregate blend was kept as 5.0 kg. Aggregates were mixed before placing the entire sample as a conical pile into the cylindrical mold of the VB apparatus. The conical pile was flattened using the scoop to achieve a flat surface. The plastic plate attached at the base of the surcharge is then carefully lowered and positioned on the flat surface. The distance between the bottom of the plastic plate and the internal base of the mold was calculated using the average of four different points. Following this initial setup, the VB apparatus was vibrated for the compaction of the aggregate sample. The vibration period of 45 s was found to be an appropriate time for compaction of most of the aggregate combinations [34]. However, the vibration period of 10 s was kept for the binary aggregate blends with fine content of 80% and higher. The reduced time was chosen as the significant amount of sand started to move above the plastic plate for the vibration period higher than 10 s. The bulk packing density (γ) of the aggregate blends was calculated using the following equation:

$$\gamma = \frac{4000\,W}{\pi\, D^2 (H - \Delta h)}$$

where γ is the bulk packing density of combined aggregate (kg/m^3); W is the weight of the aggregate blend (5 kg); H is the height of container (mm); Δh is the reduction in height for compacted aggregate (mm) (Δh = 0 for the loose state of aggregates). The packing degree (PD) of loose and compacted aggregate state was determined using the following equation:

$$\varphi = \gamma . \sum_{i=1}^{n} \frac{A_i}{\rho_i}$$

Where φ is the packing degree of the combined aggregate (%); A_i is the volume proportion of the individual aggregate (%); ρ_i is the grain density of the individual aggregate (kg/m^3); γ is the bulk packing density of combined aggregate (kg/m^3), and n is the number of individual aggregates in the combined blend.

Figure 4. Vee-Bee apparatus [33]

Analytical Evaluation of Packing Degree

Analytical assessment of combined packing degree was conducted using discrete modified-Toufar theoretical model [23,34], and Aim & Goff model [35], based on the physical characteristics of the individual aggregate's sources (fine, coarse, or intermediate). The Aim and Goff model considers the interaction of large particles with smaller particles based on the Furnas theory [36]. Based on the Aim and Goff model, the packing degree was calculated using the following two equations:

$$\varphi = \frac{\varphi_2}{1 - y_1}, \quad y_1 < y^*$$

$$\varphi = \frac{1}{\frac{y_1}{\varphi_1} + (1 - y_1) \times (1 + 0.9 * \frac{d_1}{d_2})}, \quad y_1 > y^*$$

where φ_1 and φ_2 are Eigenpacking degrees of fine and coarse aggregates, respectively; y_1 and y_2 are grain volume of the fine and coarse aggregates, and d_1 & d_2 are characteristic diameters of fine and coarse aggregates. The packing degree of individual aggregates is called the Eigenpacking degree. The y* defines the borderline between the two cases for fine and coarse aggregate dominance and is defined by the following equation:

$$y^* = \frac{p}{1 + p}$$

where p can be defined as follow,

$$p = \frac{\varphi_1}{\varphi_2} - \left(1 + 0.9 * \frac{d_1}{d_2}\right) * \varphi_1$$

Modified-Toufar model [37] assumes the larger particles (e.g., coarse, or intermediate) are distributed discretely throughout the matrix of smaller particles (e.g., fine aggregates), and the total packing degree of combined aggregates is described as the following equation:

$$\varphi = \frac{1}{\frac{y_1}{\varphi_1} + \frac{y_2}{\varphi_2} - r_2(\frac{1}{\varphi_2} - 1)k_s k_d}$$

where φ_1 and φ_2 are Eigenpacking degrees of fine and coarse aggregates, respectively; y_1 and y_2 are grain volume of the fine and coarse aggregates; k_d considers the ratio of the diameters between the coarse and fine aggregate, and k_s is a statistical factor that considers the probability of the number of interstices between four coarse particles surrounding a fine particle surrounded.

FINDINGS

Binary and Ternary Experimental and Theoretical Packing

The experimental packing degrees for the binary and ternary combination of aggregate blends are presented in Fig. 5 and Fig. 6. Binary combinations of aggregate blends include Hamburg Coarse and Clayton fine aggregates as well as Hamburg Coarse and Clayton fine aggregates. Ternary combinations of aggregate blends include Hamburg coarse, Wantage intermediate, and Clayton fine aggregates, as well as Weldon coarse, Wantage intermediate, and Clayton fine aggregates, along with Weldon coarse, Weldon intermediate, and Clayton fine aggregates.

For the binary system, the best experimental packing degree was achieved as 77.30% and 77.70% for a relatively fine blend of the Hamburg and Weldon series, respectively. The fine aggregate volume percent pertaining to the highest packing degree was found to be both 60% and 50% for Hamburg and Weldon series, respectively. The modified-Toufar model predicted a slightly higher value of packing degree than experimental values for Hamburg and Clayton blends.

On the other hand, for Weldon and Clayton blends, the modified-Toufar model closely agrees with the experimental values.

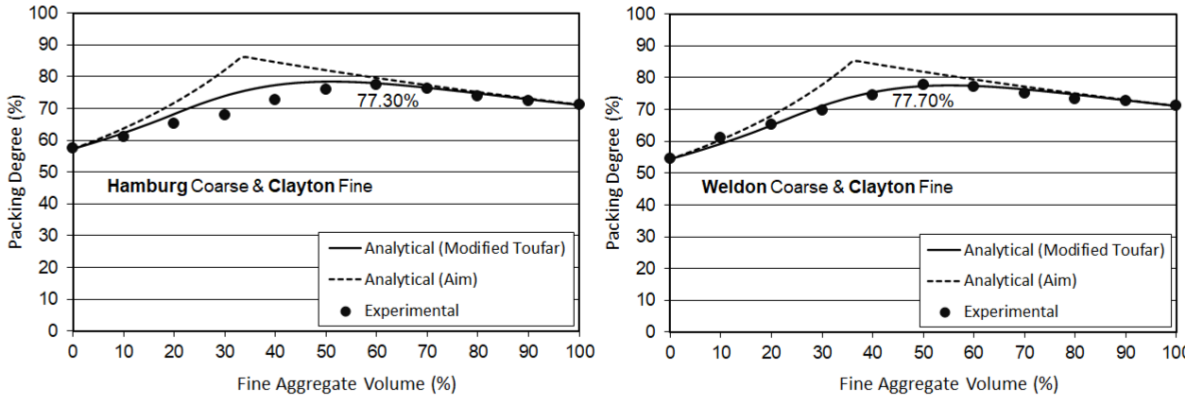

Figure 5. Experimental and theoretical packing degree for binary aggregate combination.

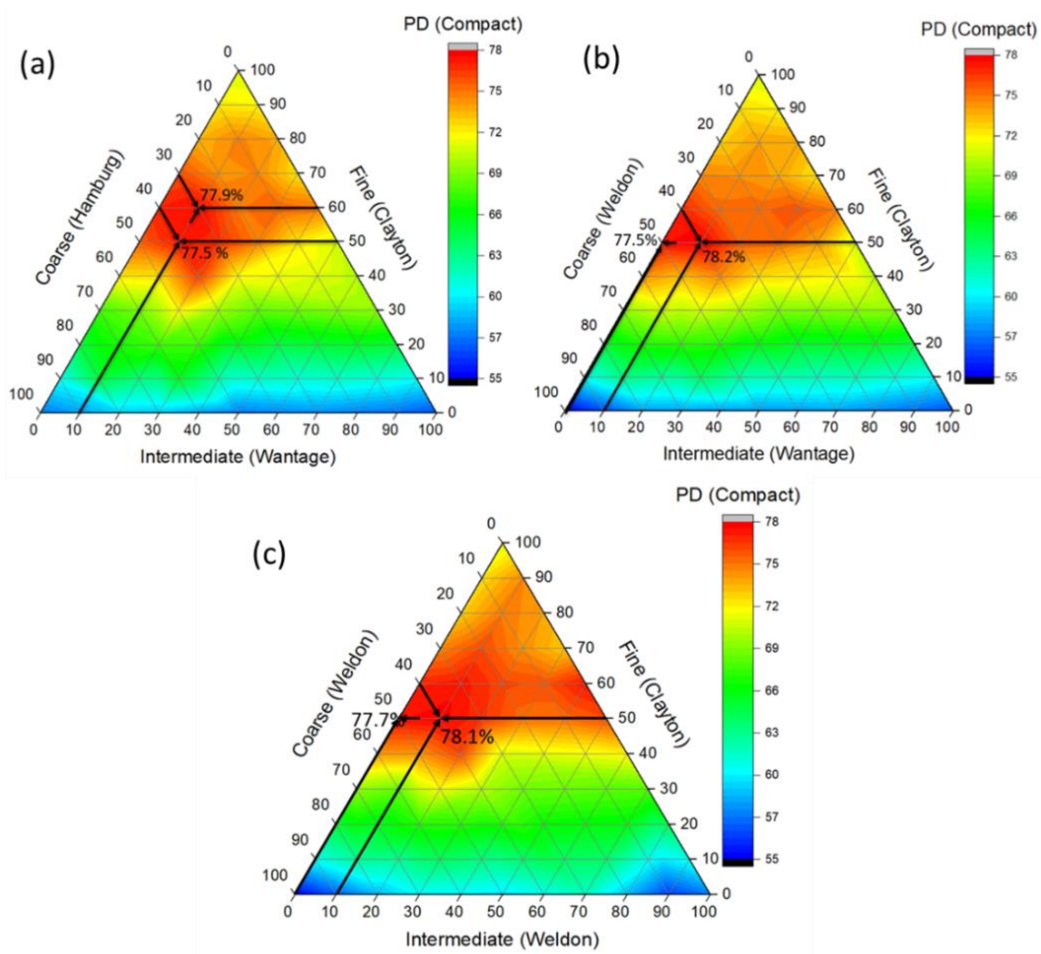

Figure 6. Experimental packing degree for the ternary aggregate combination of (a) Hamburg Coarse, Wantage Intermediate, and Clayton Sand (b) Weldon Coarse, Wantage Intermediate, and Clayton Sand (c) Weldon Coarse, Weldon Intermediate, and Clayton Sand.

For the ternary systems, it was observed that the packing degree was slightly improved with the substitution of 10% coarse aggregate with the intermediate aggregate from the optimal binary blend. Interestingly, the multiple peaks of packing degree were observed in the case of both the Hamburg and Weldon series. For the Hamburg-Wantage-Clayton combination, two peaks of 77.9% and 77.5% were observed hence forming a region of high packing degree for the fine aggregates from 50% to 60% and the intermediate aggregate of 10%. A similar pattern was observed for the Weldon-Wantage-Clayton as well as Weldon-Weldon-Clayton combinations with a high packing degree region for 50% fine aggregates and 0% to 10% of the intermediate aggregate. The corresponding peak values of packing degree for the Weldon-Wantage-Clayton combination were observed to be 77.5% and 78.2%. Similarly, the peak values of packing degree for the Weldon-Weldon-Clayton combination were 77.7% and 78.1%.

Combined aggregate gradation of optimal blends

The sieve analysis for maximum aggregate proportions with respect to packing degree for both Hamburg and Weldon has been presented in Fig. 7-9. The ASTM C33 limits for the combined aggregate were calculated by proportioning the ASTM C33 limits of individual aggregate. It was observed that the aggregates with optimized aggregate proportions comply with ASTM C33 standards [33].

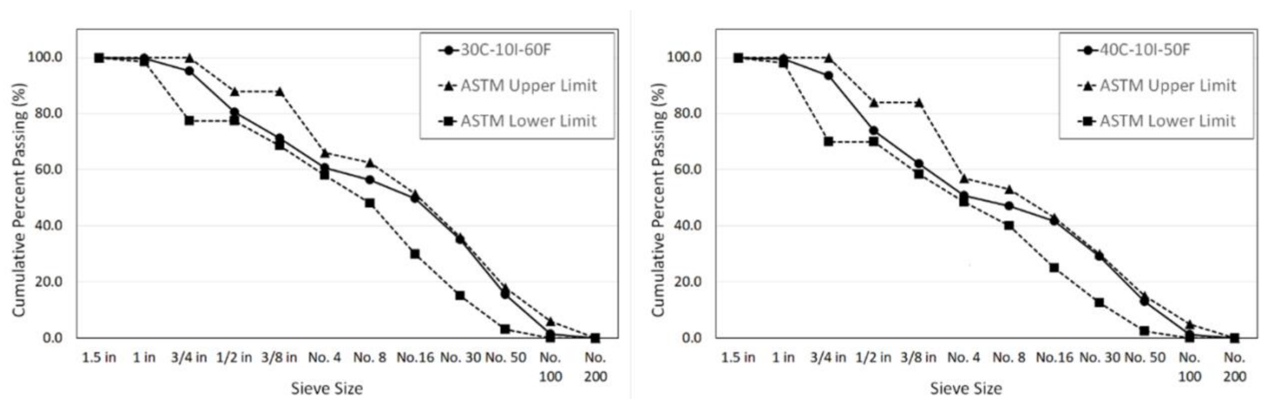

Figure 7. Sieve analysis of the maximum combined aggregate proportion of the Hamburg Coarse-Wantage Intermediate-Clayton fine series

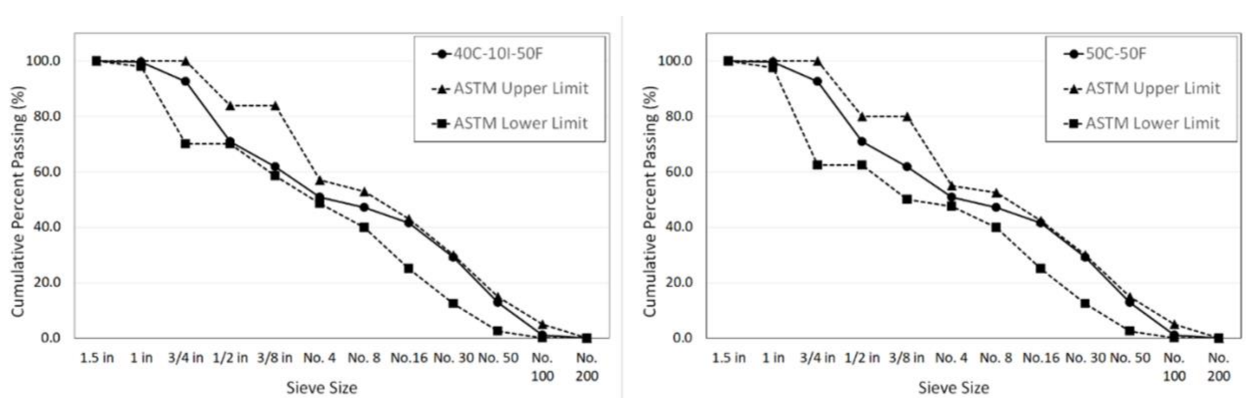

Figure 8. Sieve analysis of the maximum combined aggregate proportion of the Weldon Coarse-Wantage Intermediate-Clayton fine series

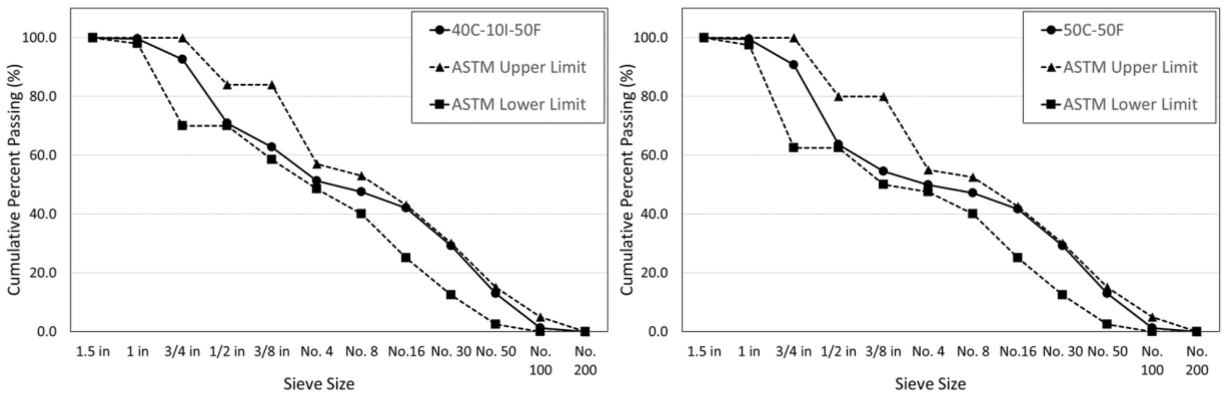

Figure 9. Sieve analysis of the maximum combined aggregate proportion of the Weldon Coarse-Weldon Intermediate-Clayton fine series

Comparison with Power Curves

Analysis of combined aggregate gradations was conducted using Fuller-Thomson Gradation curves, 0.35, 0.45, 0.5, and 0.7, the selection of which depends on the application (a.k.a. Power reference curves) [38]. Power curves 0.45 have been traditionally used for optimizing aggregate gradations in asphalt concrete mix designs and minimizing the binder content. The set of existing aggregates gradation was compared with properly selected reference power curves enabling suggestions for improved gradation by adjusting the proportions of a binary gradation and by introducing realistic proportions of Wantage and Weldon intermediate aggregate. Fig. 10 and 11 show the comparison of the particle size distribution (PSD) of combined aggregates (binary and ternary) to different power curves for the Hamburg and Weldon series, respectively. An increase in the fine content pushed the PSD of the combined binary aggregate from 0.7 to 0.45 power curve. Furthermore, the addition of intermediate aggregates into the combined aggregate blend aligned the PSD more with the power curves.

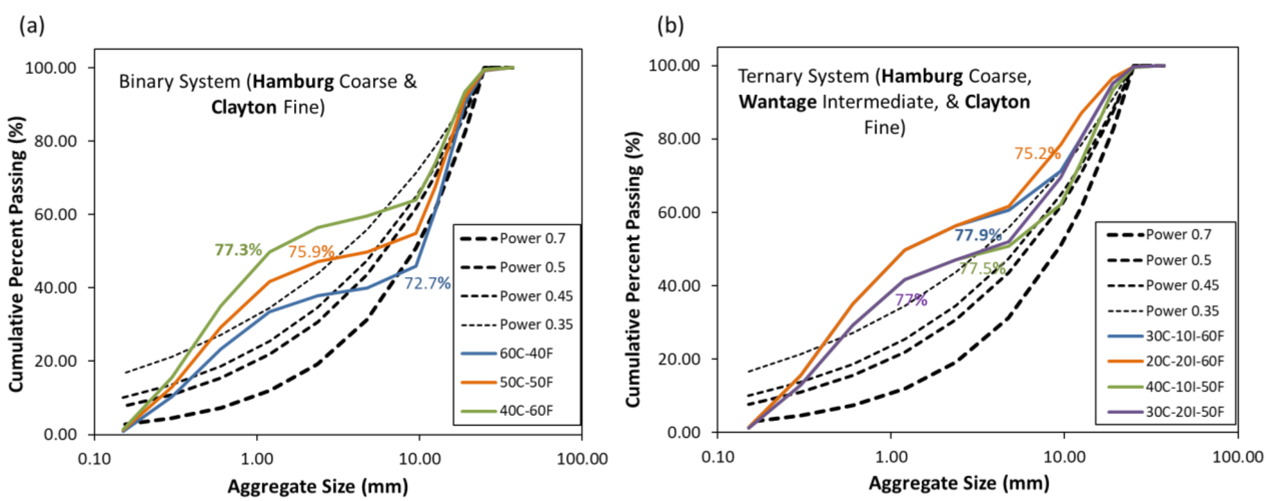

Figure 10. Particle size distribution of experimental aggregate blend of (a) Hamburg Coarse-Clayton fine series (b) the Hamburg Coarse-Wantage Intermediate-Clayton fine series (Accompanied by the Packing degree, %)

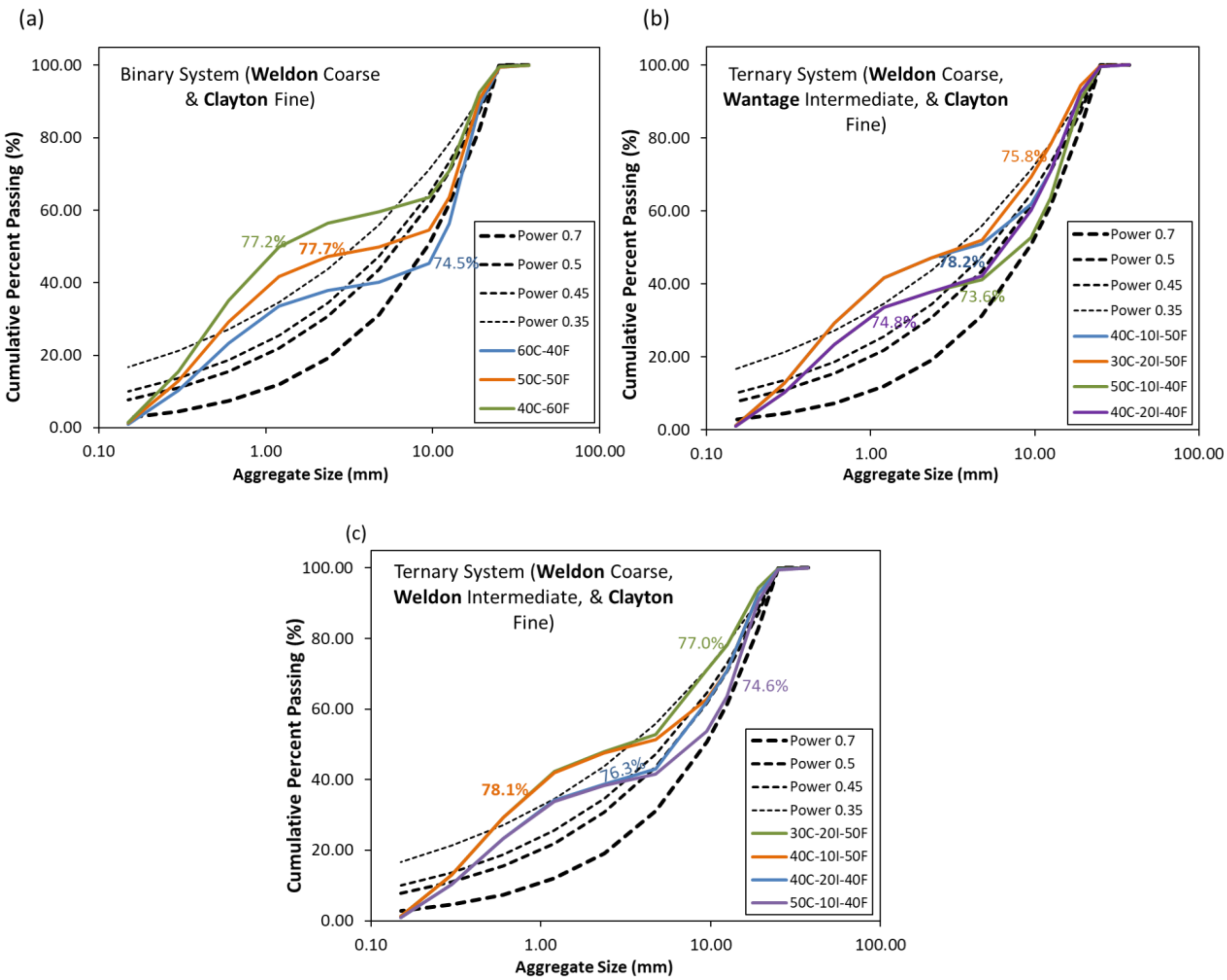

Figure 11. Particle size distribution of experimental aggregate blend of (a) Weldon Coarse-Clayton fine series (b) Weldon Coarse-Wantage Intermediate-Clayton fine series (c) Weldon Coarse-Weldon Intermediate-Clayton fine series (Accompanied by the Packing degree, %)

Shilstone Chart

The Shilstone chart specifies the Coarseness Factor (CF) and Workability Factor (WF) ranges for various blends of aggregate [15]. These charts assess the practicality of the proposed aggregate gradation. The relation between grading and concrete performance is developed by specifying a well-graded zone in the Shilstone chart as Zone II. The empirical WF and CF parameters depend on the composition, grading, and cement content of the mix and are defined as follows,

$$CF = 100 \times \frac{R_{9.5}}{R_{2.36}}$$

$$WF = P_{2.36} + 0.045 \times (C - 335)$$

where, $P_{2.36}$is cumulative percent passing from 2.36 mm (#8) sieve, C is cement content (kg/m^3), $R_{2.36}$ is cumulative percent retained on 2.36 mm sieve (#8) sieve, and $R_{9.5}$ is cumulative percent retained on 9.50 mm sieve (#3/8) sieve.

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The WF is controlled primarily by the fine aggregate content, and the CF is defined by the ratio of fine aggregates to combined fine and intermediate aggregate size groups. Table 2-4 shows the coarseness and workability factors for different blends of aggregates for the Hamburg-Wantage-Clayton, Weldon-Wantage-Clayton, and Weldon-Weldon-Clayton series, respectively. Furthermore, the data in Tables 2-4 are plotted on the Shilstone chart in Figures 12, 13, and 14, respectively. Sample points 1-3 for all the types of aggregate blends were out of the bounds of the charts, hence they were not plotted. Sample points 4-6 of all the aggregate blends have high WF reflecting high fine aggregate content and hence lie in the sandy Zone IV of the Shilstone chart.

Table 2: Coarseness and Workability Factors for the Hamburg Coarse-Wantage Intermediate-Clayton fine series

		Binder Content 660 lb/yd^3		Binder Content 500 lb/yd^3		Packing
S. No.	Aggregate Ratio	Coarseness Factor	Workability Factor	Coarseness Factor	Workability Factor	Degree (Compact)
1	40C-60F	82.7	58.9	82.7	54.7	77.3%
2	**30C-10I-60F**	**66.0**	**58.9**	**66.0**	**54.7**	**77.9%**
3	20C-20I-60F	49.3	58.9	49.3	54.7	75.2%
4	50C-50F	85.3	49.7	85.3	45.4	75.9%
5	**40C-10I-50F**	**71.5**	**49.7**	**71.5**	**45.4**	**77.5%**
6	30C-20I-50F	57.8	49.7	57.8	45.4	77%
7	60C-40F	87.1	40.4	87.1	36.2	72.7%
8	50C-10I-40F	75.4	40.4	75.4	36.2	72.8%
9	40C-20I-40F	63.7	40.4	63.7	36.2	76.7%

* C, I, and F correspond to coarse, intermediate, and fine aggregates, respectively.

Table 3: Coarseness and Workability Factors for the Weldon Coarse-Wantage Intermediate-Clayton fine series

		Binder Content 660 lb/yd^3		Binder Content 500 lb/yd^3		Packing
S. No.	Aggregate Ratio	Coarseness Factor	Workability Factor	Coarseness Factor	Workability Factor	Degree (Compact)
1	40C-60F	83.5	59.0	83.5	54.7	77.2%
2	30C-10I-60F	66.7	59.0	66.7	54.7	75.5%
3	20C-20I-60F	49.8	59.0	49.8	54.7	75.7%
4	**50C-50F**	**86.2**	**49.8**	**86.2**	**45.5**	**77.7%**
5	**40C-10I-50F**	**72.2**	**49.8**	**72.2**	**45.4**	**78.2%**
6	30C-20I-50F	58.3	49.8	58.3	45.4	75.8%
7	60C-40F	88.0	40.5	88.0	36.2	74.5%
8	50C-10I-40F	76.1	40.5	76.1	36.2	73.6%
9	40C-20I-40F	64.3	40.5	64.3	36.2	74.8%

* C, I, and F correspond to coarse, intermediate, and fine aggregates, respectively.

Table 4: Coarseness and Workability Factors for the Weldon Coarse-Weldon Intermediate-Clayton fine series

S. No.	Aggregate Ratio	Binder Content 660 lb/yd³ Coarseness Factor	Binder Content 660 lb/yd³ Workability Factor	Binder Content 500 lb/yd³ Coarseness Factor	Binder Content 500 lb/yd³ Workability Factor	Packing Degree (Compact)
1	40C-60F	83.5	59.0	83.5	54.7	77.2
2	30C-10I-60F	65.0	59.3	65.0	55.0	77.6
3	20C-20I-60F	46.2	59.7	46.2	55.4	76.5
4	**50C-50F**	**86.2**	**49.7**	**86.2**	**45.5**	**77.7**
5	**40C-10I-50F**	**70.9**	**50.1**	**70.9**	**45.8**	**78.1**
6	30C-20I-50F	55.5	50.4	55.5	46.2	77
7	60C-40F	88.0	40.5	88.0	36.2	74.5
8	50C-10I-40F	75.1	40.8	75.1	36.6	74.6
9	40C-20I-40F	62.0	41.2	62.0	36.9	76.3

* C, I, and F correspond to coarse, intermediate, and fine aggregates, respectively.

It was observed that the CF decreases with the replacement of coarse aggregate with the intermediate aggregate, however, WF remained unchanged. Based on the 660 lb/yd^3 binder content, aggregate blends with 40 % fine content and 10-20% intermediate content were positioned in the well-graded Zone II. However, it is evident from Fig. 12-14 that the WF significantly reduced with the decrease in the binder content from 660 Ib/yd^3 to 500 Ib/yd^3. This reduction pushed the samples in the sandy zone more toward Zone-II. Hence, the amount of cement can be further reduced in the mix design to use the relatively sandy mix with a higher packing degree as the optimal aggregate proportion.

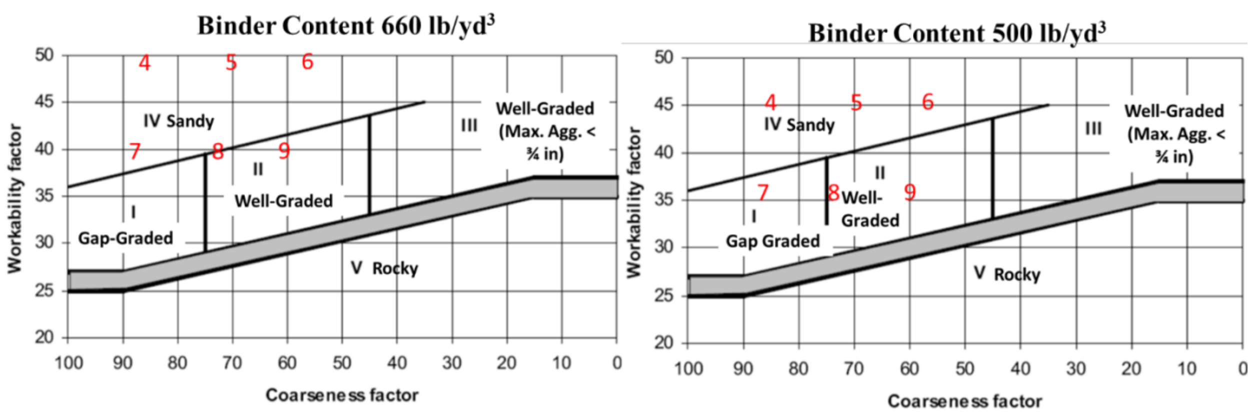

Figure 12. Shilstone chart of aggregate mixtures of Hamburg Coarse-Wantage Intermediate-Clayton fine series

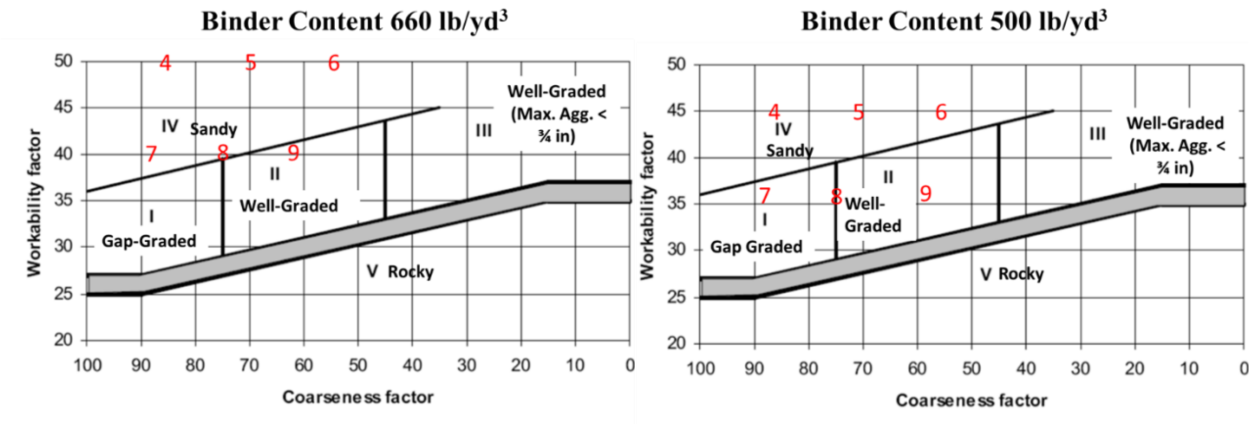

Figure 13. Shilstone chart of aggregate mixtures of Weldon Coarse-Weldon Intermediate-Clayton fine series

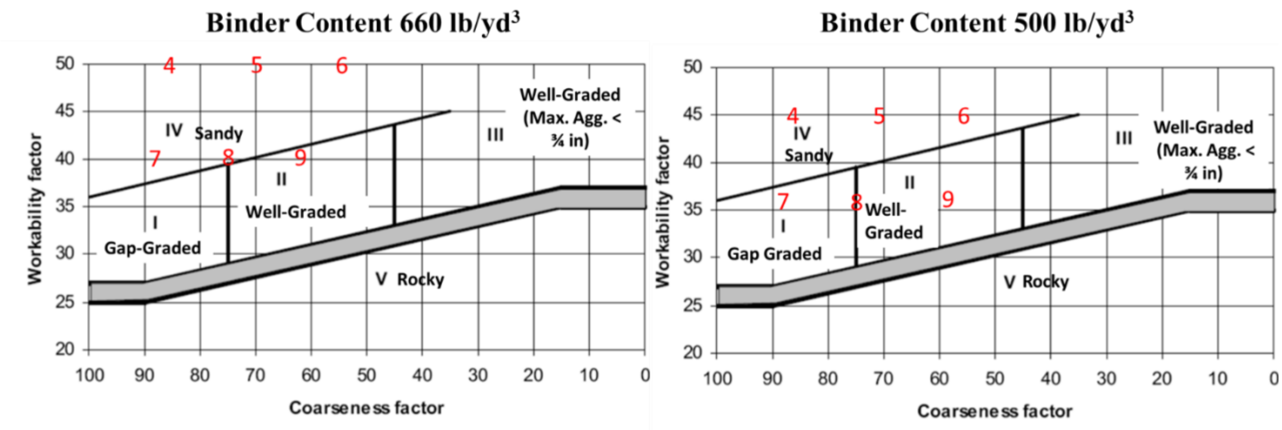

Figure 14. Shilstone chart of aggregate mixtures for Weldon Coarse-Weldon Intermediate-Clayton fine series

CONCLUSIONS

Multiple criteria were used to evaluate the effect of packing density on concrete performance. The aggregate packing was used as a criterion to optimize the aggregate blends of concrete. The power curves served as an additional criterion to optimize the blend. The Shilstone chart assisted in expanding the level of workability and coarseness factors of the blends with binary or ternary aggregates. The chart was used to study the aggregate blends for the mixtures with various cement contents and aggregate combinations in terms of field application.

The experimental results of binary aggregates (using Hamburg coarse aggregate and Clayton fine aggregate) showed the highest packing degree of 77.3% represented in a blend of 40% coarse and 60% fine aggregates. The highest packing degree values (using Weldon coarse aggregate and Clayton fine aggregate) were found to be 77.5% in a blend of 50% coarse and 50% fine aggregate. The results obtained from the modified-Toufar theoretical model closely matched the experimental results. Furthermore, it was observed that the 10% of substitution of coarse aggregate with the intermediate aggregates, from the best binary mix proportions, slightly improves the packing degree, for both the Hamburg and Weldon ternary series.

Power curves were used as an effective tool for the optimization of aggregate proportions. The mixtures with higher fine aggregate contents were fitted to smaller power curve exponents such as 0.35–0.45, while mixtures with a lower volume of fine aggregates were closer to 0.5–0.7 power gradings. It was also observed that the addition of 10% intermediate aggregates leads to better particle packing evident from the better fit to the power curves. This finding was corroborated with the values of experimental and theoretical packing.

Finally, Shilstone charts provided insight into the practical handling of the various blends in terms of workability and coarseness factors for practical cement contents including typical and reduced cement content concrete. It shows that the best aggregate proportions stay at the boundary of fine and well-graded regions whereas baseline mix designs stay in gap-graded regions for the 500lb/ft^3 of cement content.

Based on the aggregate PD, power curves, and Shilstone chart, the volumetric 40% coarse, 10% intermediate, and 50% fine has been reported as the best aggregate proportion for both Hamburg coarse and Clayton fine aggregate blends and Weldon coarse and Clayton fine aggregates). This aggregate proportion have PDs ranging from 77.5-78.2% for different combinations of coarse, intermediate, and fine aggregates. The PDs for the best optimized binary and ternary blends are significantly higher than the PDs of the field concrete (mix number: 1435, 1455, 1621, 2048, 3680, 11813, 3107, 1523, 3743, & 2473) with aggregate blends with typical binary proportions ranging from 33-47% fine and corresponding 67%-53% coarse aggregates which leads to 71.2-76.8% PD (calculated based on experimental results). These baseline mix designs have a binary combination of Weldon coarse and Clayton fine aggregate with an average fine content of around 40%.

RECOMMENDATIONS

The use of ternary aggregate blends is recommended to help improve the packing degree and reduction of cementitious binders. In addition, binary blends with 50-60% fine aggregates content depending on the type of aggregates, are reported to achieve the highest packing. For the ternary systems, it was observed that the packing degree was slightly improved with the substitution of 10% coarse aggregate with the intermediate aggregate from the optimal binary blend. The use of ternary aggregate blends assists with the gradation which enhances the consistency of the mix and potential challenges involved in practical field applications. Further work on laboratory and field concrete needs to be accomplished to assess the viability of cement reduction and development of guidelines for the amounts of practical reductions.

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