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USE OF MODIFIED ANDREASEN MODEL FOR LOW CEMENT CONCRETE OF MEDIUM STRENGTH

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ABSTRACT:

Concrete usage has tremendously increased in the past few decades with cement being the 2nd most widely used material next to water. Cement and concrete industry is alone responsible for more than 5% of global anthropogenic CO_2 emissions. With global pressure mounting for fighting climate change requires an ever increasing need to optimize concrete mix proportions to reduce cement consumption whilst maintaining durability. Optimization of concrete mix proportion over the decades has been achieved with the help of various particle packing models. The aim of the research is to study the effect on strength and durability of mixes optimized using Modified Andreasen Particle Packing Model with cement content lower than specified by building codes. The results on strength and durability of optimized mix were compared with convention concrete mix. It was found that concrete mixes optimized by Modified Andreasen Model performed better if not worse than conventional ACI concrete mix with fly ash, although prepared with significantly lower cement content.

KEYWORDS: Particle Packing Models, Modified Andreasen Model, Low Cement Content, Durability

1. Introduction

Cement by mass is the most manufactured product in the world and is the 2nd most used material only next to water. Cement production over the last 65 years has seen a 34-fold increase while human population has increased only 3-fold [1]. This increment in cement production is directly related to an increase of standard of living of people around the world. In 2015 alone, 4.6 billion tons of cement was produced world over is responsible for more than 30% of global material consumption [1].

Over the years researchers have been able to reduce cement usage in concrete through various means such as use of supplementary cementitious materials (SCM), use of fillers, chemical admixtures and developing better mixture proportioning methods, but their usage has been limited by various standards and codes. With concrete and cement industry responsible for more than 5% of global anthropogenic CO_2 production, there is a growing need to optimize the concrete mix proportions to reduce the cement content while retaining performance and durability [2].

Optimization of mixture proportions with particle packing models (PPM) along with the use of hydraulic or blended cement and SCM can have a significant impact on immediate reduction of CO_2 emissions. Also, if durability can be achieved, the long-term prospects of such mix proportion methods become more viable.

Particle Packing Models in mixture optimization have been discussed over the past century with various researchers coming up with different models. PPM can generally be classified into two models: Discrete and Continuous Models.

Kumar and Santhanam [3] define discrete models as a packing system containing two or more discrete size classes of particles where the coarsest size class forms the skeleton of the mixture while "continuous model approach assumes that all size classes are present in the particle distribution system, that is, discrete approach having adjacent size classes ratios that approach 1:1 and no gaps exist between size classes" [3]. Continuous packing approach is of significance in mixture proportioning as most of the materials used in concrete at least in theory are assumed to be and designed as continuous particle size distribution systems [4].

1.1 Continuous Particle Packing Models

The first continuous PPM was introduced by Fuller and Thomson in 1907 [5]. They proposed the ideal gradation curves for maximum density and is known as the Fuller's Curve and derived the following equation Eq. (1):

$$CPFT = \left(\frac{d}{D}\right)^{n} 100 \qquad (1)$$

where,

CPFT	=	cumulative (volume) percent finer
n	=	0.5, later revised to 0.45
d	=	particle size
D	=	the maximum particle size

This work was continued by Andreasen whose work was also based on packing of particles [3]. Andreasen's approach was theoretical and in part represents the theory of particle packing [6]. As per Andreasen the smallest particle in a mixture are infinitesimally small and derived the following equation Eq.(2) [7].

$$CPFT = \left(\frac{d}{D}\right)^{q} 100 \qquad (2)$$

where,

CPFT	=	cumulative (volume) percent finer
q	=	the distribution coefficient
d	=	particle size
D	=	the maximum particle size

Dinger and Funk [7] recognized a fundamental problem with the Andreasen Model, the smallest particle in a mixture cannot be infinitesimally small and went on to modify the Andresen's equation to accommodate the size of the smallest particle in the mixture and is represented by equation Eq.(3) [7]. Figure 1 illustrates the ideal packing curves for Fuller, Andreasen and Funk and Dinger.

$$CPFT = \frac{(d^q - d_0^q)}{(D^q - d_0^q)} 100 \qquad (3)$$

where,

CPFT	=	cumulative (volume) percent finer
q	=	the distribution coefficient or exponent
d	=	particle size
d_0	=	the minimum particle size in the distribution
D	=	the maximum particle size

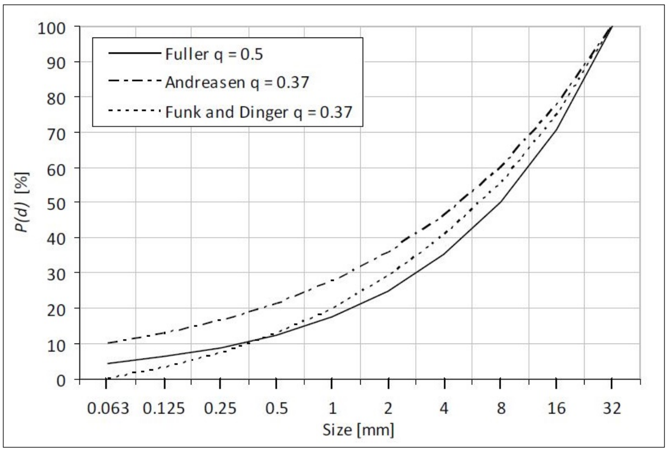

Figure 1 Ideal packing curves for Fuller, Andreasen and Funk and Dinger [3]

According to the authors, the densest packing of a mixture can be achieved with a distribution coefficient q of 0.37 which shall result in lower binder content and better hardened properties [4]. For q factor beyond 0.37, the porosity increases significantly but for q factor below 0.37 the same trend is not noticed [8]. Kumar and Santhanam while working with the Modified Andreasen Model, noted that depending on the rheological requirements of the concrete mixture, the distribution factor q can be varied from 0.21- 0.37, with 0.21 for concrete mixes with very high workability requirements (i.e. self-compacting concrete mixes) and 0.37 for very dry mix like roller compacted mixes, while conventional concrete mixtures can have distribution coefficient's in between these values [3].

Most of the work on concrete mixtures designed using particle Modified Andreasen Model have high to moderate amount of cement [4]. Similarly, there is minimal data on the durability of such mixes designed using PPM quantifying the durability aspect of medium strength structural concrete with low cement content (200 kg/m3) [9] or with hydraulic cement and fly-ash.

1.2 Scope of Work

The objective of this work was to analyze the effects of various distribution co-efficient of the Modified Andreasen PPM to produce concrete of medium strength with low cement content. For the purpose, three distribution coefficients (q) were chosen and the fresh (slump), hardened (compressive strength) and durability (sorptivity, chloride ion penetrability and abrasion) properties of the various mixtures were compared. All the mixes were compared with concrete produced with conventional method as per ACI 211.1 with fly-ash usage as per ACI guidelines.

2. Materials and methodology

2.1 Raw Materials

Cement used was hydraulic cement Type- GU (General Use) (TIS 2594 similar to ASTM C1157 having a specific gravity of 3.04. Local Class F fly ash with a specific gravity of 2.67. Specific gravity of cement and fly-ash was determined as per ASTM C188. Local river sand was selected for the study with a fineness modulus of 2.5 and a specific gravity of 2.42 and with a bulk density of 1,481kg/m3. Locally sourced limestone aggregate was selected with specific gravity of 2.69 and bulk density of 1550 kg/m3. Aggregate classification was done as per ASTM C127 and ASTM C128 for coarse and fine aggregate, respectively.

2.2 Mixture Proportions

Theoretically, distribution coefficient of 0.37 gives the densest mixture, but during trial mixes it was observed that the any mix above 0.34 was very difficult to work with, due to poor workability. Similarly, mix with distribution co-efficient below 0.25 had very high workability and slump flow similar to self-compacting concrete. Hence, three distribution coefficients q were selected, 0.25, 0.30 and 0.33 based on workability of the trial mixes as the scope of the paper was limited to conventional concrete. The mix proportions for particle packing mixes were determined using Elkem Materials - Mixture Analyzer (EMMA) program, which required the sieve analysis data for generating the grading curve. The sieve analysis was performed as per ASTM C136. The fourth mix of A0.25FA was produced as per ACI 211.1 using 25 % fly ash. The mixture proportions used are shown in Table 1. The same w/b of 0.50 was used. The particle distributions of all mixes are shown in Figure 2.

Table 1 Mixture proportions

Mix	A0.25FA	q 0.25	q 0.30	q 0.33
Cement (kg/m^3)	273.75	220	200	200
Fly Ash (kg/m^3)	91.25	200	163	125
Coarse Aggregate (SSD) (kg/m^3)	1007.5	970	1150	1170
Sand (SSD) (kg/m^3)	786	735	700	655
Free Water (L/m^3)	182.5	210	181.5	162.5
w/b	0.50	0.50	0.50	0.50

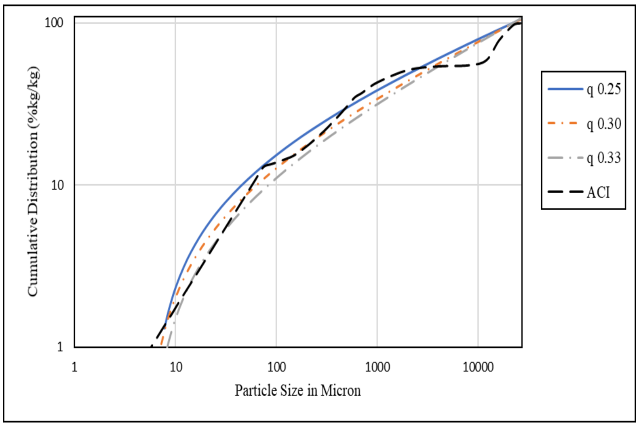

Figure 2 Cumulative particle size distribution of ACI and mixes using Modified Andreasen model

2.3 Specimen Fabrication, Curing and Testing Methods

Thirteen 100 mm by 200 mm cylindrical and one cubical 150 mm by 150 mm concrete specimen were casted for each of the four mixture proportions. Fresh property included determination of slump. Specimens were demolded after 24 hours and water cured. Hardened property test included determination of compressive strength while durability properties determined were sorptivity, chloride penetration and abrasion resistance.

Compressive strength was measured after 3, 7 and 28 days of curing as per ASTM C39. Durability tests were done after 28 days of curing. Water absorption or sorptivity was determined as per ASTM C1585, chloride ion penetrability as per ASTM C1202 and abrasion resistance as per ASTM C944.

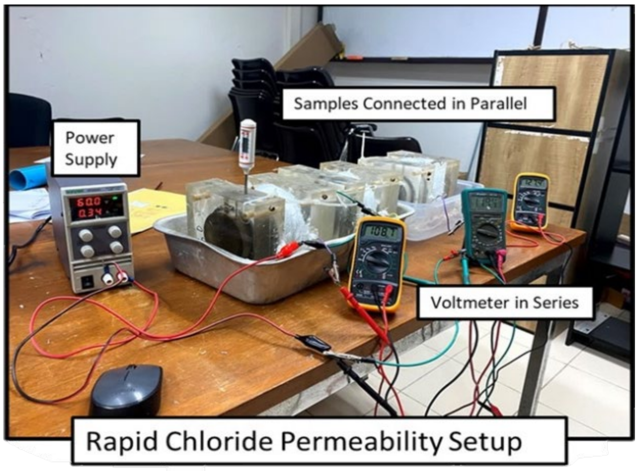

Figure 3 Setup for chloride ion penetrability test (ASTM C1202)

3. Results and Discussions

3.1 Slump

The slump determined for the mixes is shown in Table 2. From the values it was observed that the slump value of mix A0.25FA was similar to slump of mix with distribution co-efficient of 0.25. It was also observed that, q factor increased, slump value decreased for PPM mixes. The decrease in the slump for the PPM mixes was due to the better packing of constituents as q value increased and approached 0.37 [4].

3.2 Compressive Strength

The compressive strength of the mixes is shown in Table 3 and the strength development with age is shown in Figure 4. It was observed that, at an early age, mix A0.25FA has higher compressive strength and can be due to the presence of higher cement content, but compressive strength of all PPM mix after 28 days was higher than the A0.25FA mix. The higher compressive strength for PPM mixes with significantly lower cement content and can be explained by hydration of cement and fly ash along with better packing of the constituents. As the q factor increased and approached 0.37 the compressive strength also increased signifying, better packing could lead to higher compressive strength [3] [4] [18].

Table 2 Slump of ACI and PPM mixes

Mix	Slump (mm)
A0.25FA	160
q 0.25	185
q 0.30	80
q 0.33	48

Table 3 Compressive strength of ACI and PPM mixes in MPa

Mix	3-Day	7-Day	28-Day
A0.25FA	22.19	29.29	35.13
q 0.25	16.56	22.72	37.10
q 0.30	17.72	24.51	37.49
q 0.33	18.37	28.13	39.14

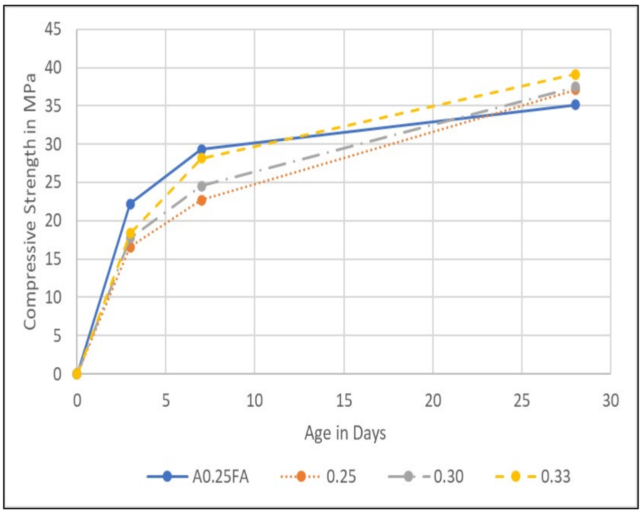

Figure 4 Compressive strength development with age

3.3 Rate of Water Absorption/Sorptivity

Rate of water absorption or sorptivity was determined as per ASTM C1585 and the results are shown in Table 4 and Figure 5. It was observed that as q value increased sorptivity decreased due to the better packing of the constituents [3,4,10]. The sorptivity of A0.25FA mix was between mix q 0.25 and q 0.30. The presence of higher amount of binder in mix q 0.25 did not contribute to lower sorptivity. Sorptivity for PPM mixes was directly related to the better packing of the mixes as q increased [3,4,11].

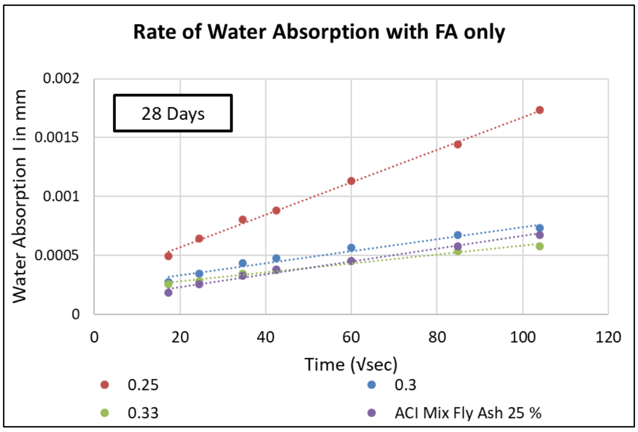

Figure 5 PAC Grout Compressive Strength

Table 4 Compressive strength of ACI and PPM mixes in MPa

Mix	Sorptivity (mm/√sec)
A0.25FA	0.0542×10^{-4}
q 0.25	0.1381×10^{-4}
q 0.30	0.0510×10^{-4}
q 0.33	0.0381×10^{-4}

3.4 Chloride Ion Penetrability

The chloride ion penetrability was determined as per ASTM C1202. The total charge passing through the samples is shown in Table 5 and the ASTM limits for chloride ion penetrability is shown in Table 6. The PPM mixes perform better than the A0.25FA mix as the total charge passing through ACI mix was very high when compared to the PPM mixes even though the cement content was significantly lower. The presence of fly-ash also improved chloride ion penetration resistance in all the mixes [12-13], but PPM mixes still displayed better chloride ion penetration resistance due to better particle packing. For the PPM mixes, it was seen that as the q value increased the charge passing through the samples decreased which provided better chloride ion penetrability and it was related to the better packing of the constituents as q value increased [4].

Table 5 Total charge passed for ACI and PPM mixes

Mix	Charge Passed (coulomb)
A0.25FA	2430
q 0.25	1642
q 0.30	1063
q 0.33	917

Table 6 Limits for chloride ion penetrability (ASTM C1202)

Chloride Ion Penetrability	Charge Passed (coulomb)
High	>4000
Moderate	2000-4000
Low	1000-2000
Very Low	100-1000
Negligible	<100

3.5 Abrasion Resistance

The abrasion resistance of concrete was determined as per ASTM C944 and the mass lost by the specimen is shown in Table 7. From the mass lost by the specimens it was seen that A0.25FA mix performed better when compared to PPM mixes q 0.25 and 0.30, while q 0.33 mix performed better than the rest. It was also noted that as q value increased the mass loss due to abrasion reduced and was due to better packing and the lower content of fines in the PPM mixes with higher q value. Figure 6 illustrates abrasion test setup.

Table 7 Mass Loss due to abrasion for ACI and PPM mixes

Mix	Mass Loss (g)
A0.25FA	8.83
q 0.25	11.75
q 0.30	9.25
q 0.33	6.50

Figure 6 Abrasion test as per ASTM C944

4. Conclusions

The research was aimed towards evaluating the use of Modified Andreasen Model to produce structural concrete of medium strength with low cement content and good durability. For the purpose three distribution factors (q) were selected and various properties were evaluated and compared with mix produced using conventional mix design procedure of ACI 211.1. The following conclusions were drawn from the results.

1. Distribution factor q controls the fresh, hardened and durability properties of concrete produced using Modified Andreasen Model. As q factor increased from 0.25 to 0.33, compressive strength and durability improved and while slump decreased.

2. Early age compressive strengths of Modified Andreasen mixes were lower than that of conventional concrete and was due to the lower cement content in the mix.

3. Modified Andreasen Model can be used to improve 28-day compressive strength and durability related properties of concrete mixtures with low cement content (200 kg/m3).

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