Computer Aided Expert Knowledge System for the Design of Concrete Mixes

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***Abstract*-Optimal proportions of concrete mix ingredients are vital for establishing a relationship between the best particle distribution and the corresponding degree of packing. The maximum strength is attained when the porosity of the granular structure is minimal to the minimum voids ratio.**

Concrete is a particulate material, and the particle-packing theory has significance when designing a concrete mix. The objective of this work was to produce an optimum concrete mix of required design stipulations based on combinations of optimized aggregate grading and effective estimation of the required water and cement.

The present work investigated the potential of the particle-packing phenomenon to optimize the cement and water content and improve concrete properties with an "aggregate to paste" approach.

Keywords- Concrete; Concrete Mix Design; Trial Batch; Computer Aided Design; Optimum; Packing; Concrete Technology

I. INTRODUCTION

A good gradation implies that a sample of aggregates contains all the standard fractions of aggregate in the required proportions such that the sample contains minimum voids. A well graded aggregate containing minimum voids requires a minimum amount of paste to fill the voids in the aggregate. Minimum paste means less quantity of cement and less quantity of water, which means increased economy, higher strength, less shrinkage, and greater durability.

This concept is based on the performance of a concrete mix being optimized by maximizing the packing density of the aggregate particles and the cementitious materials. Conventional mix design methods are not capable of coping with complexities at various stages of mix design; therefore, a new mix design method is necessary for making better concrete.

In this paper, the concept of packing density, i.e. the ratio of the volume of solids to the bulk volume of the solid particles, was introduced. This concept plays an important role in modern concrete mix design because of the increasing awareness that maximization of packing density by adjusting the grading of the whole range of solid particles, including the coarse aggregate, the fine aggregate, and the cementitious materials, improves the overall performance of the concrete mix.

II. RESEARCH SIGNIFICANCE

Herein, a number of new theories regarding particle packing, which are transforming conventional concrete technology into modern concrete science, are presented. These theories have the potential to develop a more scientific and systematic concrete mix design method for the production of high-performance concrete with minimum cement consumption.

A. Concept of Packing

The degree of packing is expressed in terms of the amount of solid aggregate particles per unit volume. The mathematical expression is simply unity minus porosity. Packing density is defined as the ratio of the solid volume of the aggregate particles to the bulk volume occupied by the aggregate. Particle packing models are based on the concept that voids between larger particles would be filled by smaller particles, thereby reducing the volume of voids and increasing the packing density.

III. LITERATURE REVIEW

The packing of particles is of significance in the design of concrete. Some of the earliest research into particle packing was done by Feret, in 1892, and Fuller and Thompson, in 1907. The complexity of particle packing in concrete is due to the random nature of the properties of the aggregates and their size, shape, and surface texture. There have been several different particle packing models and theories developed over the last 100 years, including those developed by Furnas, Toufar, Dewar, and Fuller and Thompson.

Fuller and Thompson [1], did the groundbreaking work of adjusting gradation to render the greatest strength and workability. They concluded that aggregate should be graded in sizes and combined with water and cement to obtain the greatest density. They developed an ideal shape of the gradation curve. Fuller and Thompson also noted that the gradation that

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gave the greatest density of aggregates alone did not necessarily give the greatest density when combined with water and cement because of the way the cement particles fit into the smaller pores.

Wig, et al. [2], suggested that Fulller and Thompson's conclusion could not necessarily be extrapolated to aggregates different from the ones used in the original study. Their study showed that the Fuller Curve may not always give the maximum strength nor maximum density.

Talbot and Richart [3], developed the well known equation; P = [d/D]n, where, P = amount of material in the system finer than size 'd', d = size of the particular group in question, D = largest particle in the system, n = exponent governing the distribution of sizes.

Their work indicated that for a given maximum particle size D, the equation produces the maximum density, when n = 0.5. They concluded that aggregate graded in this way would produce concrete mixtures that were harsh, difficult to place, and not really usable.

Edwards [4], theorized that the surface area of aggregate particles controlled the amount of water required for a workable concrete mixture. The controlling factors were the characteristics of the cement and the fine aggregate surface area.

Young [5], further discussed the concept that the quantity of water required was dependent on the quantity and consistency of cement and the total surface area of the aggregate, which in turn was dependent upon the grading. He concluded that the concrete aggregate having the least surface area required the least water in excess of that required for the cement and thus was the highest in strength.

Abrams [6], published his now-famous work regarding concrete mix design. He stated that there was a relationship between aggregate grading and the quantity of water required to produce workable concrete. To aid in the selection of aggregate gradations that would prevent the use of excessive water, he developed a method of representing aggregate gradation known as the Fineness Modulus (FM).

Weymouth [7], based his theory on the size of the space between particles and the next smaller size that would fit into that space. For maximum workability and the greatest economy, the relationship between particle sizes should be one in which particles of one size group are just smaller than the opening provided by the next larger particle group.

According to Shilstone [8], there are three factors that should be used to determine the optimum combination of aggregates. These factors include the coarseness factor, workability factor and 0.45 chart. The mortar factor is the amount of mortar, sand and paste required for a particular construction classification. The coarseness factor is the percent of plus No.8 material retained in the 3/8 sieve, and the workability factor is the percent passing through a No.8 sieve.

Shilstone [8], recommended calculation of aggregate gradations based on volume rather than the traditional weight basis. This makes more sense because particles interact volumetrically, not by weight.

Anishchik and Medvedev [9], took an interesting approach to dense packing; it involved the solution of the three-dimensional Apollonian problem using the Voronoi - Delaunay method based on non-equal spheres. In this method, a new sphere is packed into the Voronoi S-region (the region of a volume all points of which are closer to the surface of a given sphere than to the surfaces of other spheres in the packing). Using this approach, a very high packing degree of 90% was achieved using a relatively small number of particles.

IV. DEVELOPMENT AND APPLICATION OF NEW CONCRETE MIX DESIGN METHOD

The general approach of all existing methods of concrete mix design is to identify a starting set of mix proportions following the standard country code guidelines based on paste to aggregate estimation, and by making adjustments to the proportions after every trial mixes until the desired mix requirement parameters are satisfied.

Hence, there is a need to overcome the limitations of existing methods by developing a new theory of concrete mix design based on aggregate to paste instead of paste to aggregate. To solve the task of the concrete mix design and obtain optimization, a new theory of concrete mix was proposed with the help of a spread sheet program as shown in Flow-Chart-1 and elaborated in the following important stages.

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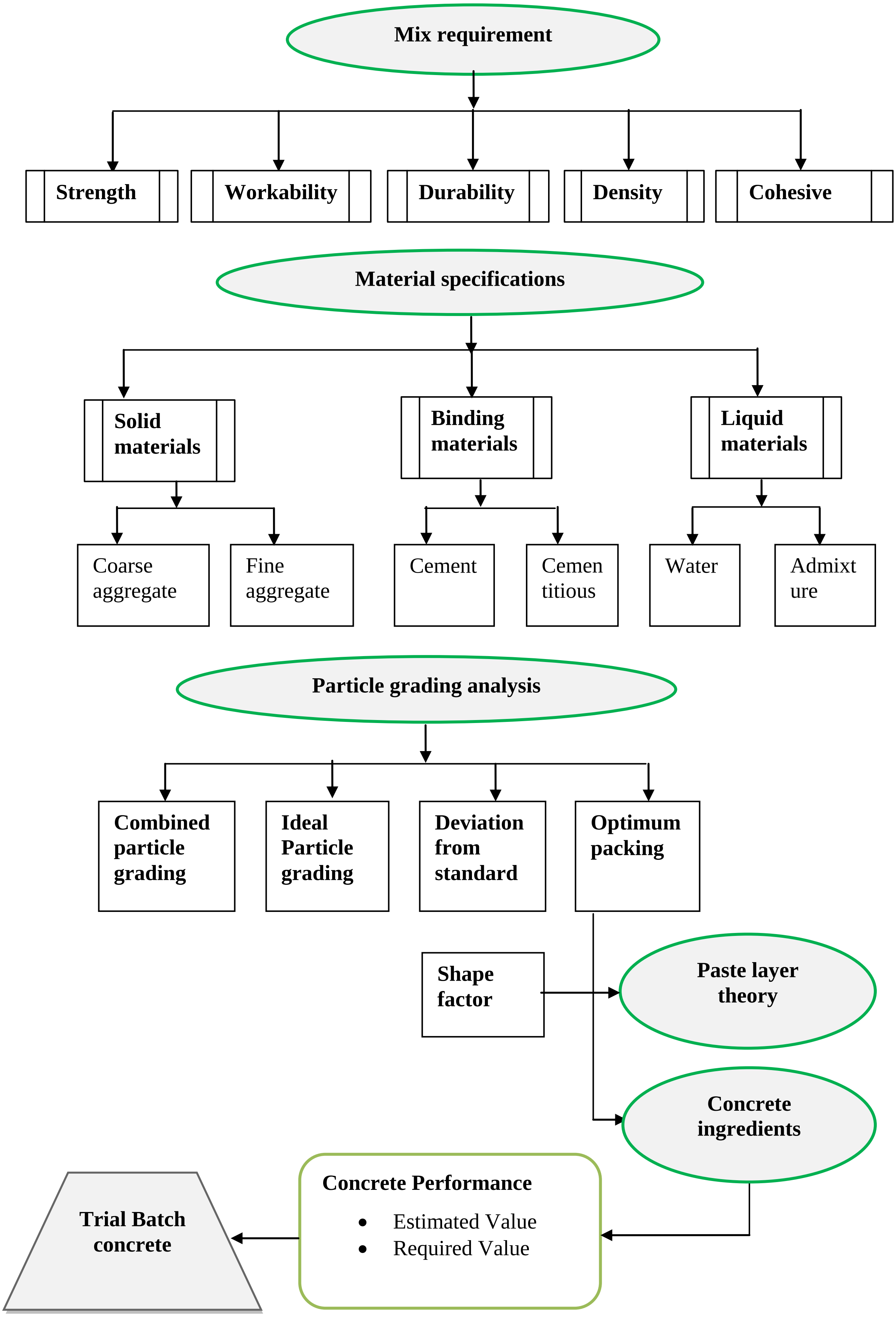

Flow-Chart-1 Proposed theory of concrete mix design

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Stage-1] Mix details [A];
Stage-2] Mix requirement [B];
Stage-3] Material specifications [C];
Stage-4] Particle grading analysis [D];

- Ideal Grading Curves [E];
- Combined Particle Grading Curves [F];
- Particle shape factor [G];

Stage-5] Paste layer theory [H];
Stage-6] Concrete ingredients estimation [I];
Stage-7] Parameter guidelines [J];
Stage-8] Required parameters [K];
Stage-9] Estimated parameters [L];
Stage-10] Trial batch [M]

In the present work, concrete mix designs were carried out based on the new method proposed for M20, M40 and M60 grades of concrete, and are elaborated on step-wise with the screenshot in this section.

A. Mix Details

Concrete mix design is generally done for specific site conditions. Here, the details of the mix were denoted as Mix-ID, client name, project name, and date of design, as shown in Fig. 1, which shows as screenshot of the mix requirements and materials specifications.

B. Mix Requirement

A concrete mix design is a multi-objective optimization process in which the objective is to design economical concrete mixes that satisfy the specific mix requirements of strength, workability, exposure type and density properties taken into account for the available concrete constitute properties of fine aggregate, coarse aggregate, cement, admixtures, and water with optimum utilization.

All these parameters are standardized with codification, classifications and the minimum and maximum ranges values. The mix strength classification and codification are as mentioned in Table 1. Workability, exposure conditions, and density of the mix are similarly shown in Tables 2, 3, and 4, respectively.

TABLE 1 STRENGTH CLASSIFICATION AND CODIFICATION

Sr. No.	Class	Strength type	Range/Values	Unit
1	S-1	Low	10 to 30	MPa
2	S-2	Medium	31 to 50	MPa
3	S-3	High	51 to 70	MPa
4	S-4	Very high	> 71	MPa

TABLE 2 WORKABILITY CLASSIFICATIONS AND CODIFICATION

Sr. No.	Class	Workability type	Range/Values	Unit
1	W-1	Very Low	< 25	mm
2	W-2	Low	26 to 50	mm
3	W-3	Medium	51 to 75	mm
4	W-4	High	76 to 100	mm
5	W-5	Very high	101 to 125	mm
6	W-6	Large	➢ 125	mm

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TABLE 3 EXPOSURE CONDITIONS [DURABILITY] CLASSIFICATION AND CODIFICATION

Sr. No.	Class	Exposure type
1	E-1	Mild
2	E-2	Moderate
3	E-3	Severe
4	E-4	Very Severe
5	E-5	Extreme

TABLE 4 DENSITIES OF MIX CLASSIFICATION AND CODIFICATION

Sr. No.	Class	Density type	Range/Values	Unit
1	D-1	Light	1500 to 1800	MPa
2	D-2	Medium	1801 to 2100	MPa
3	D-3	Normal	2101 to 2400	MPa
4	D-4	Heavy	2401 to 2700	MPa

In the present work, concrete mix design was carried out for M20, M40, and M60 grades of the concrete for the following mix requirement parameters, Strength M20, M40, and M60; Workability medium (75 to 100 mm); Durability moderate; Density of mix medium (2000 Kg/m^3); and Concrete type reinforced cement concrete [RCC], as shown in Fig. 1.

C. Material Specifications

The concrete constitutes are broadly classified into three types including solid material, binding material, and liquid material. Their physical properties are as shown in Fig. 1. It is very important to understand the physical properties of the materials in order to produce a better concrete mix design.

- **Solid material**: The coarse aggregate and fine aggregate are considered solid materials. Physical properties like shape, size, type, moisture content, water absorption, and particle sieve analysis are mentioned.
- **Binding material**: The cement and cementitious materials are considered binding materials. Physical properties like grade, specific gravity, particle size and cost per m^3 are mentioned.
- **Liquid material**: The water and chemical admixtures are considered liquid materials. The use of admixtures and their effects are mentioned.

D. Particle Grading Analysis

Grading is the most important geometrical characteristics, and is defined as the relation between the sieve size X(I) in mm and the sieve cumulative passing Y(I) in percentage. It determines the relative content of particles with different dimensions. Particle grading analysis is carried out for fine and coarse aggregates, as shown in Fig. 2. Aggregates are classified based on particle sizes as the following:

- Coarse aggregate: 40mm/20mm/10mm
- Medium aggregate: 4.75mm/2.36mm/1.18mm
- Fine aggregate: 0.6 μ / 0.3 μ
- Ultra-fine aggregate: 0.15 μ / 0.075 μ

From particle grading analysis, the following parameters are estimated:

- Particle grading curve, fineness modulus
- Grading zone of fine aggregate
- Maximum aggregate size of coarse aggregate
- Oversize and undersize fractions, class of aggregates

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S-1 Mix Details

Mix-ID	Mix-001
Client	
Project	
Date	18/03/12

S-2 Mix Requirements

Strength [Mpa]	M-20
Workability	Medium (75-100mm)
Durability	Moderate
Density of Mix [Kg/m3]	
Concrete Type	R.C.C.

S-3 Material Specifications

1] Cement

Type	O.P.C. [Ordn. Portl. Cement]
Grade	43
Std. Devn	5
Sp. Gravity	3.05
Cement %age	100

Total Cementious: 0

2] Cementious

	Fly-Ash	Microsilica	Metakaoline	Blast-Slag	Rice Husk	Surkhi	Others
Source							
Sp.Gr.							
Particle Size [mm]							
Cost/m3							
%age							

3] Fine Aggregate

	F.A-I	F.A.-II
Source		
Type	Natural	Artificial
Sp.Gr.	2.4	2.6
D.L.B.D. [Kg/m3]	1600	1770
Mositure Content %ag	10	5
Water Absorption %ag	2.3	2.6
Shape	Rounded	Irregular
Silt %age	5	2
Bulkage %age	2	1
%age Replacement	60	40
Cost/m3		

Sieve	F.A-I Wt. Retain	F.A.-II Wt. Retain
40.00 mm	0	0
20.00 mm	0	0
10.00 mm	0	55
4.75 mm	8	137
2.36 mm	250	112
1.18 mm	277	218
600 µ	170	230
300 µ	95	170
150 µ	90	68
Pan	110	10

4] Coarse Aggregate

	C.Agg-I	C.Agg.-II
Source		
Size	20 mm	10 mm
Sp.Gr.	2.7	2.8
D.L.B.D.	1440	1390
Water Absorption %ag	1.18	1.61
Type	Crushed	Un-Crushed
Shape	Angular	Angular
%age Replacement	40	60
Cost/m3		

Sieve	C.A.-I Wt. Retain	C.A.-II Wt. Retain
40.00 mm	0	0
20.00 mm	0	0
10.00 mm	2670	2665
4.75 mm	2030	1735
2.36 mm	0	435
1.18 mm	0	0
600 µ	0	0
300 µ	0	0
150 µ	0	0
Pan	0	0

Fig. 1 Screenshot of mix requirement and material specifications

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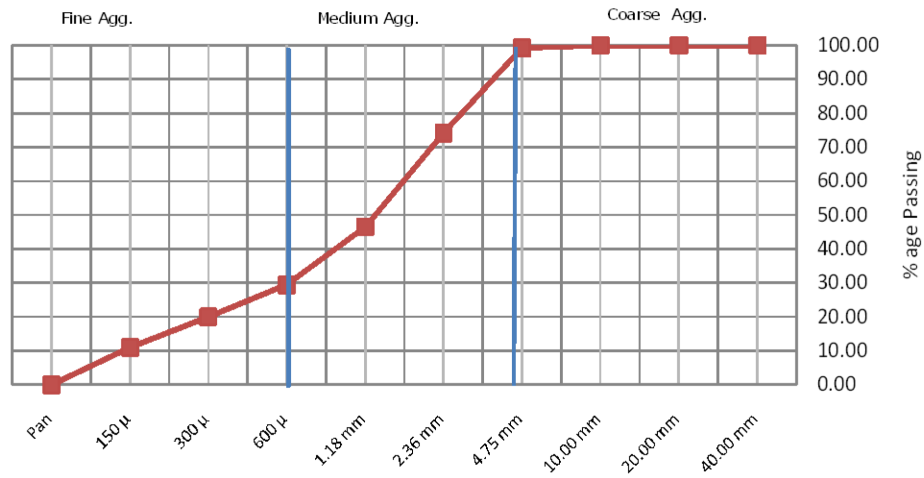
S-4 **Particle grading analysis of fine aggregates**

F.A.-I

Sieve	Weight	% age	Cumulative	% Pass	Remark
40.00	0	0.00	0.00	100.00	
20.00	0	0.00	0.00	100.00	
10.00	0	0.00	0.00	100.00	
4.75	8	0.80	0.80	99.20	0.80
2.36 mm	250	25.00	25.80	74.20	
1.18 mm	277	27.70	53.50	46.50	
600 µ	170	17.00	70.50	29.50	Zone-I
300 µ	95	9.50	80.00	20.00	
150 µ	90	9.00	89.00	11.00	
Pan	110	11.00	100.00	0.00	
Total	1000				

Results	
F.M.	3.20
Grading	Zone-I
Oversize	0.80
Remark	Coarse Agg.

Particle Grading Curve



F.A.-II

Sieve	Weight	% age	Cumulative	% Pass	Remark
40.00	0	0.00	0.00	100.00	
20.00	0	0.00	0.00	100.00	
10.00	55	5.50	5.50	94.50	
4.75	137	13.70	19.20	80.80	19.20
2.36 mm	112	11.20	30.40	69.60	
1.18 mm	218	21.80	52.20	47.80	
600 µ	230	23.00	75.20	24.80	Zone-I
300 µ	170	17.00	92.20	7.80	
150 µ	68	6.80	99.00	1.00	
Pan	10	1.00	100.00	0.00	
Total	1000				

Results	
F.M.	3.74
Grading	Zone-I
Oversize	19.20
Remark	V-Coarse Agg.

Particle Grading Curve

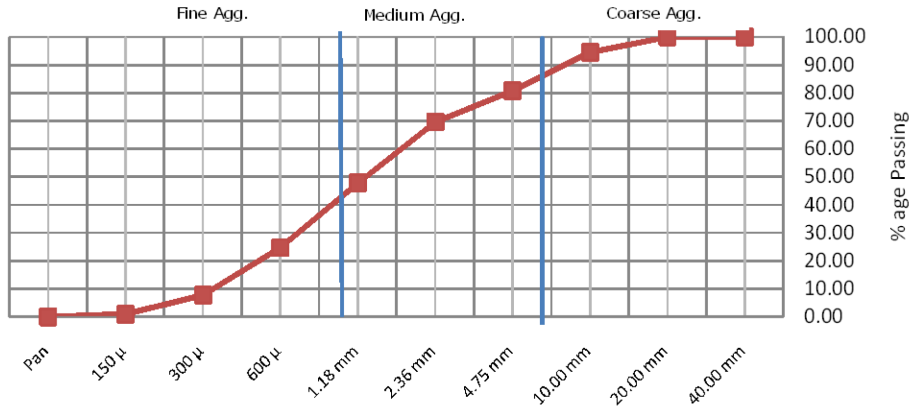


Fig. 2 Screenshot of particle grading analysis of fine aggregates

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E. Ideal Grading Curve

A typical ideal grading curve is one that provides good aggregate packing with minimum voids. In the present work, standard grading curves were developed for 40mm, 20mm, and 10mm aggregate with a packing degree (n) of 0.45, as shown in Fig. 1. The actual combined grading curves were compared to the ideal grading curves.

F. Combined Particle Grading

The various fractions of aggregates are ultimately combined as a solid material during the casting of a concrete mix. The fine and coarse aggregate fractions can be combined in various combinations. The proportions are estimated based on method least square between target curve and actual combined curves, and as shown in Fig. 3.

S-4.1 **Ideal Particle Grading Curves**

Sieve Sizes [mm]	% age Passing for [n=0.45]				
	40 mm	30 mm	20 mm	15 mm	10 mm
40	100.00	100.00	100.00	100.00	100.00
20	73.20	83.32	100.00	100.00	100.00
10	53.59	61.00	73.20	83.32	100.00
4.75	38.33	43.63	52.37	59.60	71.53
2.36	27.98	31.85	38.22	43.51	52.22
1.18	20.48	23.32	27.98	31.85	38.22
0.6	15.11	17.20	20.64	23.49	28.19
0.3	11.06	12.59	15.11	17.20	20.64
0.15	8.10	9.22	11.06	12.59	15.11
0.075	5.93	6.75	8.10	9.22	11.06

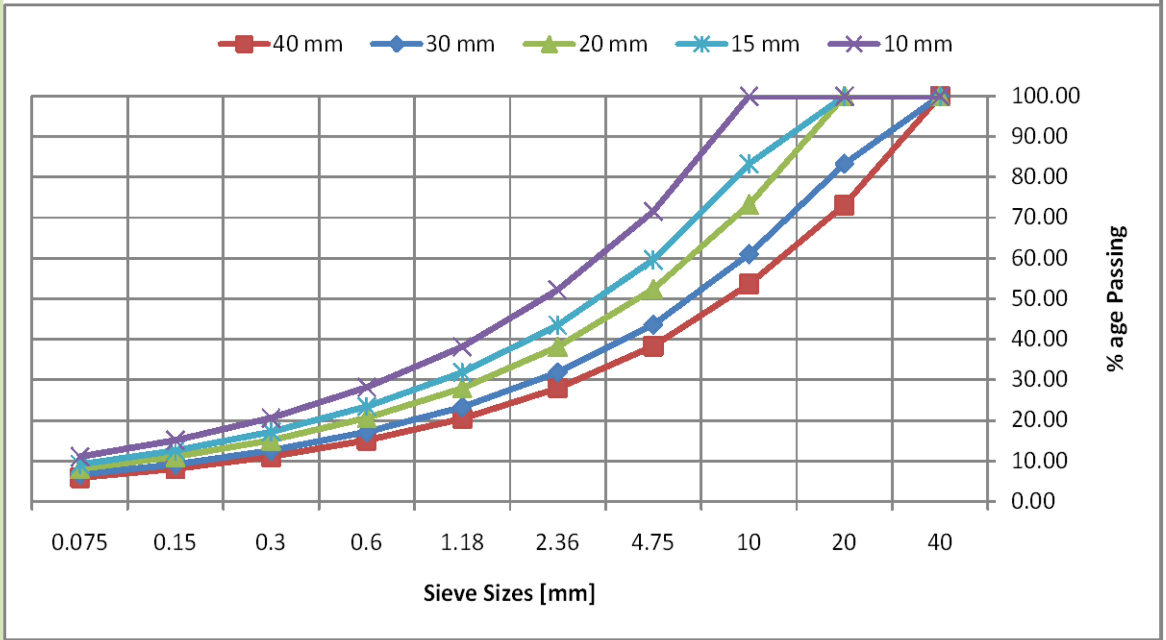

Fig. 3 Screenshot of ideal particle grading curves

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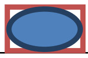
G. Particle Shape Factor

The conventional methods only consider the general characteristics of aggregates, i.e. fineness modulus, which does not completely describe the properties of aggregate.

C.F. Moraa, et al. [10], applied the digital image processing (DIP) technique to analyse the particle size distribution of coarse aggregate. A size correction factor is used to convert the particle sizes measured by DIP to equivalent square sieve sizes so that a comparison between the DIP and mechanical sieving results can be made. The study demonstrated that DIP is a fast, convenient, versatile, and accurate technique for particle size distribution analysis.

The shape factor proposed here describes the three dimensional aspects of a particle. The following shape factors were established for different types of aggregates, as shown in Table 5.

TABLE 5 PARTICLE SHAPE FACTORS

Sr. No.	Particle shape	Particle description	Shape factors		
			L	W	H
1		Rounded	1	1	1
2		Irregular	1.4	0.75	0.75
3		Angular	0.9	0.9	1
4		Flaky	2	0.5	0.5

H. Paste Layer Theory

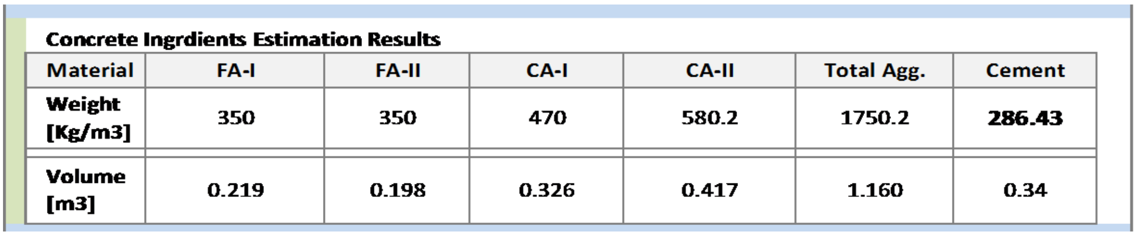
In the present method, the number of particles under each particle size is estimated based on the weight retained to the unit particle volume and accordingly, the space of the voids between them is worked out for proportions of aggregates.

The solid particles in the concrete are bound to the cementitious material by the addition of water. The paste layer is a film around the particles and forms a coating to the surface area of aggregate particles based on the particle size, its surface area, and the shape of the aggregates. However, the conventional methods of mix design estimates the required quantity of water based on fineness modulus (FM) of the aggregate, and no weightage is given to the important geometrical properties of particles (particle size, its surface area, and shape of aggregates).

The granulation coefficient parameter is used to characterize the aggregate grading composition and shape of particles. The parameter used here was to estimate the content of cement to form a paste around the particles. The quantity of water and cement estimated on the basis of the paste layer theory to coat the specific surface area of each particle, is 1mm thick water film for fine aggregate and 2mm for coarse aggregates. The thickness of the water film may vary depending on the workability requirement.

I. Concrete Ingredients Estimation

Basic ingredients of concrete are estimated based on the concept of optimum aggregate combination with maximum particle packing of minimum voids and optimum thickness of paste layer to coat the aggregate particle and fill the voids, as shown in Fig. 4. Here, the approach of design was aggregate to paste instead of the paste to aggregate approach of conventional methods.



Concrete Ingrdients Estimation Results

Material	FA-I	FA-II	CA-I	CA-II	Total Agg.	Cement
Weight [Kg/m3]	350	350	470	580.2	1750.2	286.43
Volume [m3]	0.219	0.198	0.326	0.417	1.160	0.34

Fig. 4 Screenshot of Concrete ingredients estimation

J. Parameters Guidelines

To satisfy the multi-objectives function parameters set at the start of concrete mix design, a correlation between various parameters involved in the mix design as individual components and combined components with their effects on plastic and hardened state of concrete were established by classification of each objective parameters into sub-classes and minimum requirement values over different ranges for each class.

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The parameter's requirement guidelines were proposed based on standard guidelines of ISI, ACI and DOE methods of concrete mix design. The range of constituents and ratio of different parameters are provided for mix strength, mix workability, mix durability, and mix density, and as shown in Tables 6 through 9.

TABLE 6 MIX STRENGTH REQUIREMENT PARAMETERS GUIDELINES

Class	Strength	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
S-1	10 to 30 MPa	210	600	800	200	NA	1.6	1810
S-2	31 to 50 MPa	310	700	900	175	-	1.7	2085
S-3	51 to 70 MPa	410	800	1100	150	-	1.8	2460
S-4	> 71 MPa	510	900	1300	125	-	1.9	2835

TABLE 7 MIX WORKABILITY REQUIREMENT PARAMETERS GUIDELINES

Class	Slump	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
W-1	Very Low (< 25 mm)	NA	500	NA	125	NA	2	NA
W-2	Low (26-50 mm)	-	550	-	150	-	1.9	-
W-3	Medium (51-75 mm)	-	600	-	175	-	1.8	-
W-4	High (76-100 mm)	-	650	-	200	-	1.7	-
W-5	V.High (101-125 mm)	-	700	-	225	-	1.6	-
W-6	High (126-150 mm)	-	750	-	250	-	1.5	-

TABLE 8 MIX DURABILITY REQUIREMENT PARAMETERS GUIDELINES

Class	Durability	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
E-1	Mild	210	NA	800	NA	0.5	1.5	NA
E-2	Moderate	285	-	900	-	0.45	1.6	-
E-3	Severe	360	-	1100	-	0.4	1.7	-
E-4	V-Severe	435	-	1200	-	0.35	1.8	-
E-5	Extreme	510	-	1300	-	0.3	1.9	-

K. Required Parameters

The feasibility of the obtained concrete mix can be checked in terms of mix strength, mix workability, mix durability, and mix density by comparing them to the required parameter values with estimated parameter values of mix design based on available material specifications. The required parameter values for different mix requirements are minimum cement, fine aggregate, coarse aggregate, water cement ratio (WCR), cement water ration (CWR), and density of mix, as shown in Fig. 5.

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TABLE 9 MIX DENSITY REQUIREMENT PARAMETERS GUIDELINES

Class	Concrete density [Kg/m3]	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
D-1	Light (1500 - 1700)	NA	NA	800	NA	NA	NA	1500
D-2	Medium (1700 - 1900)	NA	-	900	-	-	-	1700
D-3	Normal (1900 - 2100)	NA	-	1100	-	-	-	1900
D-4	Heavy (2100 - 2300)	NA	-	1200	-	-	-	2100
D-5	V-Heavy (2300 - 2500)	NA	-	1300	-	-	-	2300

	Class	Mix Requirement	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
A]	Mix Strength								
	S-1	10 to 30 MPa	210	600	800	200	NA	1.6	1810
B]	Mix Workability								
	W-3	Medium (51-75 mm)	NA	600	NA	175	NA	1.8	NA
C]	Mix Durability								
	E-2	Moderate	285	-	900	-	0.45	1.6	-
D]	Mix Density								
	D-3	Normal (1900 - 2100)	NA	-	1100	-	-	-	1900

Fig. 5 Screenshot of required parameter values

L. Estimated Parameters

The estimated parameter values based on particle packing and paste layer estimation were as shown in Fig. 6, taken into consideration for the feasible solution of optimum particle packing of aggregate in the concrete mix.

Mix Estimation for M20 Grade of Concrete	Min. Cement [Kg/m^3]	Min. FA [Kg/m^3]	Min. CA [Kg/m^3]	Min. Water [Kg/m^3]	Min. WCR	Min. CWR	Min. Density [Kg/m^3]
Estimated	245.69	600	906.5	180	0.73	1.36	1932.19
Final estimation	285.00	600	906.5	175	0.61	1.63	1966.50

With Aggregate % of Particle Grading Analysis	FA-I	FA-II	CA-I	CA-II
	30.00	30.00	9.00	10.00

Fig. 6 Screenshot of estimated parameter value

M. Trial Batch

The optimum solution obtained after satisfying the mix requirement parameters were compared to the trial batch. The concept of the trial batch was to determine how the concrete would act in plastic and hardened states in the sense of technical parameters, such as its strength, workability, durability, and density, being predicated based on the formulated guidelines. The strength of the trial batch was predicated based on the cement content and cement water ratio (CWR), as shown in Figs. 7 and 8.

Trial batch mix strength prediction based on cement content is expected to be 31 to 40 MPa, for M20 grade of concrete, similarly it is 31 to 45 MPa for M40 and also 31 to 45 MPa for M60 based on actual cement content respectively.

The trial batch mix strength prediction based on the CWR was expected to be 20 to 31 MPa, for M20 grade of concrete, 31 to 45 MPa for the M40 concrete, and also more than 71 MPa for the M60 concrete, based on actual the CWR.

Similarly, the workability, durability, and density of the actual concrete can be predicated based on the concept of the trial batch.

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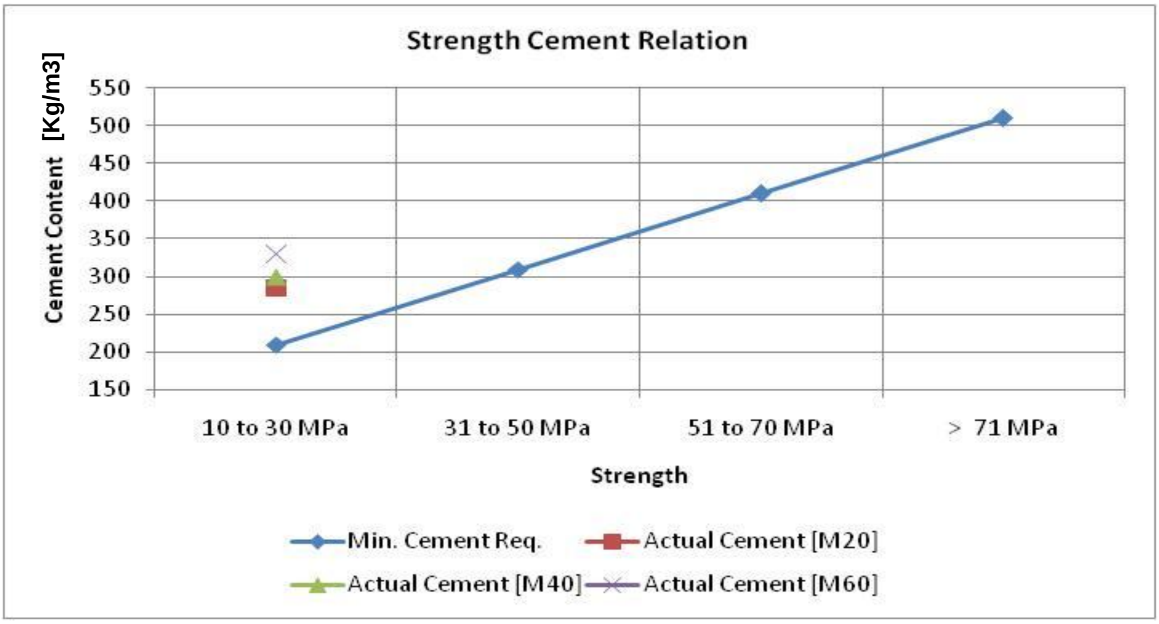

Fig. 7 Trial Batch concrete strength prediction based on cement

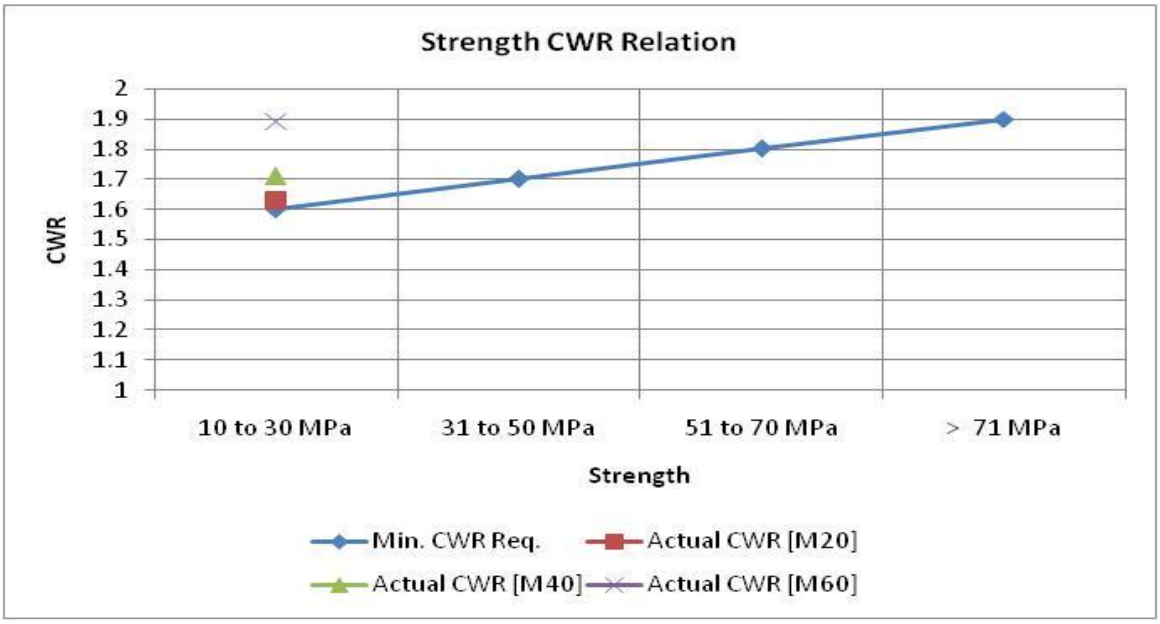

Fig. 8 Trial batch concrete strength prediction based on CWR

V. COMPARATIVE RESULTS OF NEW METHOD OF MIX DESIGN

The results obtained from traditional methods of mix design were compared to the new method of mix design, and the details were as shown in Tables 10, 11, and 12 for M20, M40, and M60 grades of concrete, respectively. In concrete mix design, the ratio of the amount of aggregate to the amount of cement used is called the aggregate to cement ration (ACR). These two ingredients are responsible for making durable, workable, and dense concrete with high strength.

TABLE 10 NEW METHOD AND CONVENTIONAL METHOD OUTPUTS FOR M20 CONCRETE

Sr. No.	Constituents	Output of mix design for 20 MPa			
		ISI	ACI	DOE	New method
01	Density [Kg/m^3]	2287	2310	2406	1966.5
02	Water [Kg/m^3]	203	215	210	175
03	Cement [Kg/m^3]	406	430	350	285
04	Total Aggregate Content [Kg/m^3]	1706	1704	1888	1506.5

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05	Coarse Aggregate Content [Kg/m^3]	903	752	906	906.5
06	Fine Aggregate Content [Kg/m^3]	802	952	982	600
07	Water Cement Ratio [WCR]	0.43	0.41	0.48	0.61
08	Aggregate Cement Ration [ACR]	4.20	3.96	5.39	5.29

TABLE 11 NEW METHOD AND CONVENTIONAL METHOD OUTPUTS FOR M40 CONCRETE

Sr. No.	Constituents	Output of mix design for 40 MPa			
		ISI	ACI	DOE	New method
01	Density [Kg/m^3]	2200	2315	2440	2269.5
02	Water [Kg/m^3]	203	215	220	175
03	Cement [Kg/m^3]	677	500	449	300
04	Total Aggregate Content [Kg/m^3]	1320	1600	1769	1794.5
05	Coarse aggregate content [Kg/m^3]	581	848	884	1094.5
06	Fine Aggregate Content [Kg/m^3]	739	752	884	700
07	Water Cement Ratio [WCR]	0.3	0.43	0.49	0.58
08	Aggregate Cement Ration [ACR]	1.95	3.20	3.94	5.98

TABLE 12 NEW METHOD AND CONVENTIONAL METHOD OUTPUTS FOR M60 CONCRETE

Sr. No.	Constituents	Output of mix design for 60 MPa			
		ISI	ACI	DOE	New method
01	Density [Kg/m^3]	2400	2400	2440	2496.2
02	Water [Kg/m^3]	203	215	220	175
03	Cement [Kg/m^3]	677	717	647	330
04	Total Aggregate Content [Kg/m^3]	1520	1468	1570	1991.2
05	Coarse aggregate content [Kg/m^3]	851	778	832	1191.2
06	Fine aggregate content [Kg/m^3]	669	690	738	800
07	Water Cement Ratio [WCR]	0.3	0.3	0.34	0.53
08	Aggregate Cement Ration [ACR]	2.25	2.05	2.43	6.03

It was observed that the new method required minimum water, cement, water cement ratio, and density for the same mix conditions of conventional methods. Hence, it is a more practical and economical method to adopt.

TABLE 13 STRENGTH VALIDATION OF CONCRETE MIX

Sr. No.	Grade of Concrete	28 days cube strength of mix			
		ISI	ACI	DOE	New method
01	M20	25	28	26	32
02	M40	44	46	42	48
03	M60	66	68	70	74

TABLE 14 WORKABILITY VALIDATION OF CONCRETE MIX

Sr. No.	Workability required	Workability of mix			
		ISI	ACI	DOE	New method
01	Medium [75-100 mm]	71	80	84	92
02		73	70	80	98
03		79	77	81	102

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The feasibility of the solution was also, proven based on a concrete cube prepared in the laboratory with available material specifications for M20, M40, and M60 grades of concrete. The results obtained for cube strength and workability are presented in Tables 13 and 14, respectively, in terms of slump of the concrete.

VI. CONCLUSIONS

Optimum mix design depends, to a large extent, on the density value and grain size distribution of the ingredients. The proposed theory provided the optimum solution for given problems. The new mix satisfied the multi-objective functions set at the start of mix design stipulations, taking into account the materials specifications constraints and their complex relations. The expert knowledge system provided an algorithm that optimized the proportions of concrete ingredients based on particle size distributions and mix design requirements.

This paper presented the result of a new mix design developed for low to high strength concrete ranging from M20 to M60 grades of concrete. It involved the process of experimentally determining the most suitable concrete mixes in order to achieve maximum strength, durability, workability, and durability with optimum use of the available material resources.

The new method proposed here took review of a concrete mix design, which should focus on the following important issues:

- Does the mix meet the performance requirements of the specifications with respect to the strength and other characteristics such as durability, workability, and density?
- Is the historical or trial batch test data adequate to justify the specific site condition mix requirements?
- Do the materials being used comply with the project requirements as evidenced by test results, certifications, and standard guidelines?

The expert system proposed here not only provides a single optimum solution, but various optimum solutions, which are more realistic for actual use in the field.

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