Optimization of Cement Mortar Mix using Digital Image Analysis: State of Art

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Abstract

Cement mortar comprises 50-90% of fine aggregates which has a significant effect on the fresh properties of the mix such as workability, adhesiveness, cohesiveness, and density. The mix characteristics depend on the aggregate properties such as the shape, size, and surface texture. The most common method used on the construction site to check the quality of the aggregate is sieve analysis. Flakiness and elongation tests are used to measure the shape characteristics of coarse aggregates only. Currently, workability for mortar is adjusted to the need either by adding water or introducing superplasticizer. It is difficult to decide cement fine aggregate proportion and dosage of admixture for the desired workability of the mix. It is possible to design mix using the surface area of fine aggregates and many researchers are working in that area. Digital Image Processing (DIP) method gives accurate information about the shape morphology of fine aggregate. One can assess the behaviour of shape characteristics of aggregates on workability. The mix design of mortar can be optimized by calculating the surface area of fine aggregates. This research paper summarizes measurement techniques to evaluate the morphology of fine aggregates, wet packing density to obtain the desired mix, and rheological aspects of cement mortar.
Keyword- Digital Image Processing (DIP), Water Film Thickness (WFT), Paste Film Thickness (PFT), Workability, Rheology, Wet-Packing Density, Interfacial Transition Zone (ITZ)

I. INTRODUCTION

The concrete contains two phases namely the mortar phase and coarse aggregate phase. The coarse aggregate phase plays a role as a filler material for concrete and it also imparts mechanical strength. The mortar phase surrounding the coarse aggregate at Interfacial Transition Zone (ITZ) is responsible for imparting workability and flowability to the concrete mix. At micro level workability is a function of water content in the mixture while the flowability is the function of cement-aggregate paste (Neville, n.d.), various studies have been carried out to study the factors which affect these properties. (Kwan and Li, 2012) pointed out that Water Film Thickness (WFT) in the fresh cement mortar is an important factor which governs the fresh properties of mortar. Paste Film Thickness (PFT) functions to provide higher flowability and has an inverse relation with cohesiveness and adhesiveness of mortar. This paper is a breakthrough for studying the behaviour of cement paste film thickness on the ITZ on coarse aggregate. As relatively higher cohesiveness and adhesion is expected from the cement paste to prevent fracture line development parallel to the face of aggregate. A balance must be established in order to achieve quality and optimizing cement in the mortar hence reducing wastage.

II. LITERATURE SURVEY

The focus of the study demands an in-depth study of two different areas namely digital image processing and the rheological behaviour of mortar and its application in workability. Hence the literature study has been divided into two parts which are as shown below.

1) Digital Image Processing a method to measure the shape characteristics of aggregate.

According to a study done by (Fernlund, 1998) on “The effect of particle form on sieve analysis: a test by image analysis” showed the disadvantages associated with the tests conducted using the traditional methods. Sieve Analysis fails to measure the size of an individual particle in a function of its form factor. The DIP method accurately measures the axial dimensions of all particles as well as the form factors and surface characteristics. The research done by (McCave & Syvitski, 1991) on Principle and Methods of geological particle size analysis shows inaccuracies in results obtained from sieve analysis. Therefore the results obtained from DIP and Sieve Analysis cannot be compared side by side. A true size or shape of particles cannot be simply measured with respect to primary dimensions units as length or width of particles, as it does not distinguish the aggregates form factor. (Wang, 1994) in theory for shape differentiation of grain size mentioned this in the study.

(Kuo, Frost, Lai, & Wang, 1996) explained a method to analyze the shape of aggregate particles forms orthogonal projections. The experiment was carried out in two steps. In the first experiment the sample was placed over a plate in its stable position and an image was taken in a plan view showing the plan area projection of the aggregates. To achieve the orthogonal projections aggregates were placed on a sample tray where two faces are kept in a perpendicular manner as shown in the Figure 1.

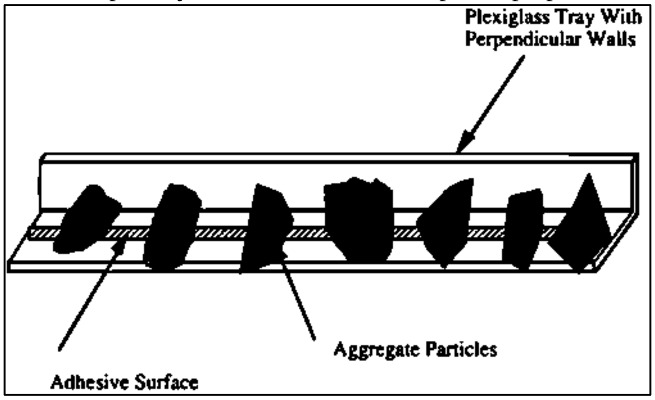

Fig. 1: Illustration of sample tray and layout of particles

Two images were taken at 0º and 90º angles to project the aggregate on each face. Following points were observed by performing an experiment. The equidimensionality of the aggregates is observed with the smallest value of elongation and flatness i.e. the values are closer to zero. Shape factors like Sphericity (Ψ) and shape factor (SF) gives an idea about the size, as it uses all the three dimensions of aggregates. Roundness uses information of area and perimeter from projected images and gives a combined expression for the shape and surface texture of particles. Particles which has higher roughness tends to have higher roundness, while fullness ratio which is often used to characterize the shape and surface texture of particles shows inverse proportionality with the extent of rough-edginess of particles. Concluding to that the author describes this method as more promising for conducting a 3D-image analysis of coarse aggregate particles, as it covers all the parameters to categorize morphological characteristics of aggregates.

A study for Particle shape analysis of coarse aggregate using digital image processing was carried out by (Kwan, Mora, & Chan, 1999) pointed out that Digital Image analysis is used because of limitation of traditional method i.e. sieve analysis which measures the lateral dimension of aggregate. Relatively flaky particles and elongated particles were also able to pass through the sieve in the orientation as shown in Figure 2 and Figure 3.Due to this reason the actual size of the particle could not be determined.

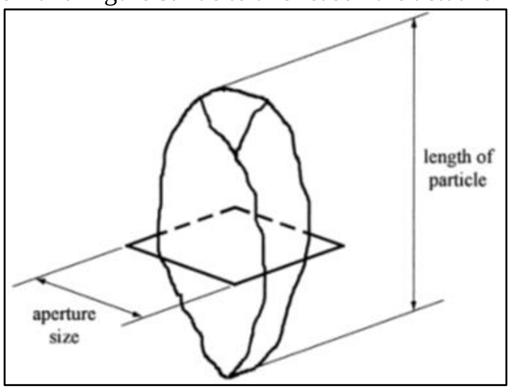

Fig. 2: Elongated Particle passing through square sieve aperture

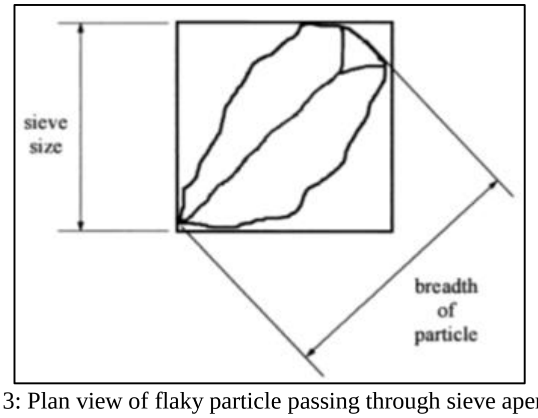

Fig. 3: Plan view of flaky particle passing through sieve aperture

In this study, the author has developed a method to carry out analysis to obtain mass fraction from the obtained area fraction. The DIP analysis carried out, has an assumption that aggregate particles having the same source have a more or less similar shape characteristics.

The shape characteristics play an important role in contributing to compressive strength of concrete says the study was done by (Polat, Yadollahi, Sagsoz, & Arasan, 2013) of The Correlation between Aggregate Shape and Compressive Strength of Concrete: Digital Image Processing Approach in which the compressive strength of aggregate is measured by varying shape characteristics of aggregate. Results show that there is direct proportionality between compressive strength and Shape factor, Sphericity and Form Factor. Aggregate which is derived from same parent rock having higher roundness has relatively higher compressive strength as compared to the ones which are angular. Apart from that the study also discusses briefly about using 3-D laser scanning technique which is very useful to measure the three orthogonal area projection to get accurate data of the area fraction of the aggregates.

Critical review of aggregate shape characteristic assessment techniques study was carried out by (Thaker & Arora, 2015), the paper provides information of different methods which are used for carrying out DIP. The selection criteria of methodology required, depends upon factors like aggregate size, accuracy and reliability of method. Each and every method has different accuracy of measurement, over the spectrum of size of particles. The data obtained from the analysis is further checked for shape describing quantities like Sphericity, Degree of Circularity, Roundness, Roughness, and Aspect Ratio, circularity, high sensitivity circularity, convexity and elongation for coarse and fine aggregates. The article further mentions the advantages of using different method on the accuracy of analyzing different shape describing quantities.

(Kumara, Hayano, & Kikuchi, 2017) in their study Evaluation of Area- and Volume-based Gradations of Sand-Crushed Stone Mixture by 2D Images evaluated the gradation curve of 2-D images. Area base gradation curve could be obtained using DIP, however the results obtained from sieve analysis was mass based gradation curve so both the results cannot be co-related. A method is proposed to compare the results by plotting volume based gradation curve with an assumption that density in the particles more or less remains the same. Figure 4 shows the setup to carry out experiment.

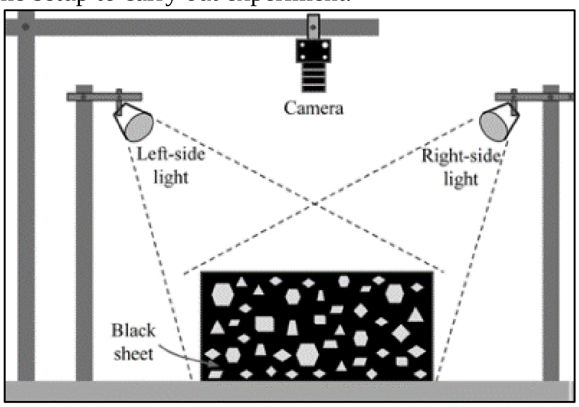

Fig. 4: Schematic diagram of particle arrangement and Image Capturing Process

A particle passing through a sieve has length and width, to compute the area a particle is assumed to be a rectangle, sphere or elliptical, and area-based curves are derived. To calculate the volume of particles the depth of particles were derived from the assumptions derived from shape characteristics of particles and iterated the same for all particles as they were derived from same parent rock.

Figure 5 and Figure 6 shows the variation in particle size distribution in terms of area and area, volume, and number based respectively. It is concluded that volume-based size distribution analysis proved to be more accurate than area-based size distribution, where assuming particle as an ellipsoid shows a more accurate result.

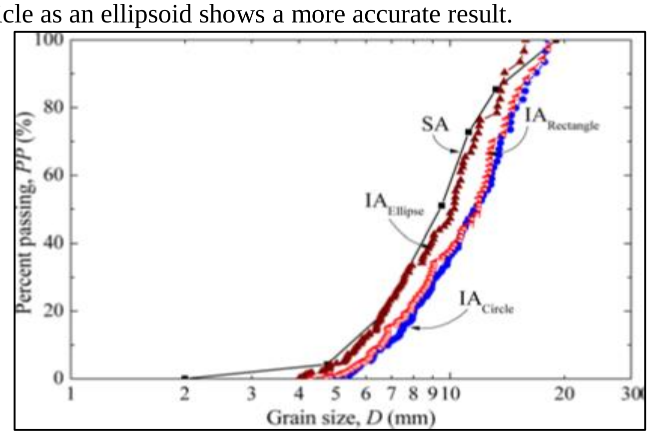

Fig. 5: Particle Size Distribution of Crushed Stone for Different Shape of Particles (SA is sieve analysis and IA is image analysis)

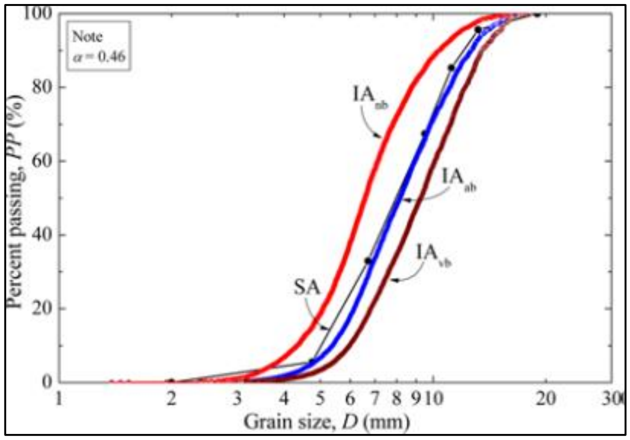

Fig. 6: Area-, Volume- and Number-based Particle Size Distributions of Crushed Stone (SA is sieve analysis, IA_{ab}, IA_{vb} and IA_{nb} are image analysis of area-, volume- and number based respectively)

2) Rheology of cement mortar and its impact on workability.

As discussed above, mortar phase plays an important role in concrete to make the mix workable, provides cohesiveness to the mixture and prevents segregation. It is the behaviour of cement paste in the medium which will be responsible for providing fluidity/flowability to concrete. Keeping these factors in mind it is necessary to study the rheology of cement mortar and the behaviour of each component individually in the matrix.

There are different types of tests available to measure workability. This is categorized on types of cement products it is been tested for i.e. concrete, grouts, paste, mortar, self-compacting concrete etc. A study carried out by (Koehler & Fowler, 2003) wrote a Summary of concrete workability test methods in which the author have discussed various advantages, disadvantages associated with the tests and what parameters are to be considered for selecting tests. The document has enlisted 61 different tests on workability which explains the concepts, working principles, and limitations. The author has laid emphasis on testing of yield stress and plastic viscosity and its significance. The author added the requirement for developing an instrument which can measure such properties in an inexpensive manner at the site as coming requirement in construction industry. Otherwise, this literature is very useful for getting a clear understanding of the working mechanism and selection criterion for each test.

(Kwan & Wong, 2008) in a two-part publication namely packing density of cementitious materials: Part 1-measurement using a wet packing method and Packing density of cementitious materials: Part 2-packing and flow of Ordinary Portland Cement + Pulverised Fuel Ash (PFA) + condensed silica fume (CSF) drew out some important findings. The author has developed a wet packing method to measure the apparent density, void content, solid concentration, and excess water present in the mixture. The author found out that for particles of sizes less than 100µ by decreasing water-cement ratio, the void ratio tends to go towards zero but then it crosses the critical point and starts increasing. Introducing water reducing admixtures decreases void ratio considerably with low water-cement ratio hence increasing packing density. Excess water content is also determined which gave rise to the concept of optimum water content requirement for covering the cement particles and voids to increase workability. The concept of Water Film thickness and Paste film thickness is discussed in the later paper.

Water Film Thickness and Paste Film Thickness: Key Factors for Mix Design of High-Performance Concrete is another study carried out by (Kwan & Li, 2008) in which concept of defining 3 tier mix design method namely paste, mortar and concrete tier is discussed. The concept was introduced in order to find out the governing factors which affect the performance of high-performance concrete (HPC). The paste and mortar tier water film thickness (WFT) is a governing factor in regulating the rheological performance of concrete. Along with it, the paste film thickness (PFT) has also a major impact on the rheological properties of concrete. The combined behaviour of WFT and PFT study is then carried out further to study the interdependency.

Combined effects of water film thickness and paste film thickness on rheology of mortar was then studied by (Kwan & Li, 2012) in which they studied the roles of WFT and PFT. WFT increase steadily with increasing cement to aggregate ratio because the mean surface area of cement increases the water demand. A thicker water film is generated around the cement particles. The PFT increases at constant rate by increasing both water cement ratio or cement aggregate ratio. The WFT or PFT increase, when the percentage increase in excess water ratio or excess paste ratio, is larger than the percentage increase in specific surface area, and vice versa. Hence proving that WFT and PFT are the key factors governing the flowability, rheology, cohesive- ness and adhesiveness of mortar. However, the WFT is still the single most important factor governing the fresh properties of mortar. Relatively large PFT will result into increase in flowability but lowers the cohesiveness and adhesiveness. Following is the procedure to determine the PFT and WFT.

Packing density of mortar has to be calculated before finding out PFT and WFT.

For the mortar mixture of total mass (M) and volume of mortar (mould) (V)

$$\text{Packing Density } (\phi) = \text{Wet Bulk Density/Solid Density} = (M/V)/\ (\rho_w u_w + \rho_c F_c + \rho_f F_f)$$

ρ_c and ρ_f are the solid densities of cement and fine aggregate. F_c and F_f are the volumetric ratios of cement and fine aggregates to the total solid content.

Void ratio is calculated by the following equation
Void ratio (r) = $(1- \phi)/ \phi$
After that, the excess water ratio is determined as the ratio of excess water volume to the total solid volume $r'=r_w-r$ (where, r_w= water/solids ratio by volume used for packing density measurement)
WFT covering each particle is determined as WFT= r'/A (Where A=Specific surface area of total solid particles= $(A_c \times F_c)$ + $(A_{FA} \times F_{FA})$).
Similarly, the PFT can be determined from the packing density of the fine aggregate particles ($\phi 1$), paste ratio p_w and the specific surface area of fine aggregate.
Here, v= voids ratio of fine aggregate particles = $(1- \phi_1)/ \phi_1$.
After obtaining the void ratio, the excess paste ratio is determined.
The excess paste ratio is the ratio of the volume of excess paste and specific surface area of fine aggregate=p'= p_w-v.
Here p_w is the paste ratio which is obtained from the ratio of paste volume to the volume of fine aggregate particles. The paste film thickness PFT= p'/A_{FA}.
(Kotak & Thaker, 2016) conducted a study on Assessment of Water Film Thickness, Paste Film Thickness and the Fresh Properties of Cement Mortar. The theory stated for the study was that the cement paste content should be sufficient enough to fill the voids formed by the fine aggregates. The water in excess can cover each solid particle and the excess cement paste covers each aggregates particles. The aim of this study was to measure the variation of water film thickness and paste film thickness by varying water-cement ratio and cement and fine aggregate proportions. The test was carried by preparing 5 different mortar mixes by varying cement sand proportion 1:1 to 1:2 with an increment of 0.25 in the sand portion for zone 1. For the mortar mixes of 1:1(C/A=1), 1:1.25(C/A=0.8), and 1:1.75(C/A=0.67) the W/C ratios were kept as 0.28, 0.30 and 0.35, while for the mixes 1:1.75(C/A=0.57) and 1:2(C/A=0.5), the W/C ratios were kept 0.4, 0.45 and 0.5. For the fine aggregate, the W/C ratio was kept at 0.55, 0.6 and 0.65 for the packing density test and 1.32% superplasticizer by weight was added. The packing density, WFT and PFT were determined. Total 15 different samples were tested for flow spread, cohesiveness, adhesiveness. The results were analysed and concluded that for a constant water-cement ratio the adhesion was lower at a lower cement-aggregate ratio, which increases to a certain limit and decreases again. To achieve good adhesiveness minimum WFT is found to be 0.071µ. And made a confirmation to the conclusion stated in the previous paper that WFT and PFT increase with an increase in Cement to aggregate ratio and water-cement ratio.

III. CONCLUSION

Digital Image Processing is an efficient method for determining the shape morphology of aggregates compared to the traditional method of sieve analysis. Sieve analysis method enables to extract information of particle size distribution in terms of mass while DIP does distribution on basis of area fraction; the solution to this problem was made afterwards by implementing orthogonal projection method for finding out the mass fraction. However, as far as the coarse aggregate is concerned this method is effective, which becomes tedious in case of finer particles. A new instrument with higher magnification could be designed to carry out this experiment or similar which can serve the purpose of measuring all the shape characteristics of coarser as well as finer particles.

The concepts of WFT and PFT can be further applied on optimization of fresh properties of concrete to serve the specific purpose of concrete. Moreover, these concepts should be applied to studying the effects of paste film properties, effects and thickness on the ITZ of aggregates, and study can be expanded to projecting it to harden properties of concrete.

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