Fracture Mechanics of Concrete and Concrete Structures -
High Performance, Fiber Reinforced Concrete, Special Loadings and Structural Applications- B. H. Oh, et al. (eds)

Verification of wet and dry packing methods with experimental data

M. Shekarchi
University of Tehran, Tehran, Iran.

S. M. Mousavi
University of Tehran, Tehran, Iran.

N. A. Libre
Islamic Azad University, Qazvin branch, Qazvin, Iran

S. Soroush-Nia
Islamic Azad University, Member of Young Researchers Club, Takestan Branch, Takestan, Iran.

ABSTRACT: It is well known that packing density of aggregate, which is related to distribution of aggregate, aggregate size, shape, and surface texture, plays an important role in performance of concrete. All existing methods of measuring the packing density of aggregate are carried out under dry condition. A new method, which measures the packing density of aggregate under wet condition, has been developed. It is called the wet packing method. Particle packing models, which are used to estimate the packing density/voids ratio of the solid combinations, can provide tools to improve the performance of concrete. In this paper, packing density of aggregate in various conditions including dry and wet packing methods were experimentally calculated. Finally, calculated results under wet conditions have been compared to those under dry ones and have been verified by theoretical models.

1 INSTRUCTION

Packing density, defined as the volume of solids per total bulk volume, which is widely used to evaluate and combine aggregates. The geometrical characteristics of shape, angularity, texture, and particle size distribution affect packing density; therefore, packing density can be used as an indirect indicator of aggregate geometrical characteristics. In general, higher packing density is preferred, although the maximum packing density may not be optimal (Johansen & Andersen 1991, Goltermann et al. 1997, Powers 1932, Powers 1968). According to (Goltermann et al. 1997) concrete mixes should have more fine aggregate than what is required for the maximum packing density. However, it should be noted that a small change in sand content does not generally cause a large change in packing density. Models for packing density have been applied for Self Compacting Concrete (SCC). SCC with near optimum aggregate packing exhibited lower viscosity, lower High-Range Water-Reducing Admixture (HRWRA) demand, and similar or greater filling capacity than SCC with slightly lower aggregate packing density (Khayat & Laye 2002). Vachon, et al. utilized the compressible packing model to select aggregates for SCC (Vachon et al. 2002). Researchers have published some mathematical models to predict packing density of powder particles (Stovall et al. 1988, Yu & Standish 1988, Yu et al. 1997, Suzuki et al. 2001, Rassouly 1999). Studies on packing and rheological behavior have been performed for no-slump concrete/ Roller Compacting Concrete (Ouellet 1997, Lahus 2001), for SCC (Noguchi et al. 1999) and for Ultra High Performance Concrete (Nehdi & Mindess 1998, Geisenhanslu & Schmidt 2004, Jacobsen et al. 2005) indicating varying empirical relations. Regarding the packing density measurements, the conventional methods, as stipulated in the existing standards, such as (Belgian Standard NBN B11-206 (1981), British Standard BS 812: Part 2 (1995), and European Standards EN 1097-3 (1998) and EN 1097-4 (1999)), measure the bulk density of the solid particles under dry condition and determine the packing density as the ratio of the bulk density to the solid density. These methods, hereafter called the dry packing methods, are widely used. For instance, (DeSchutter & Poppe 2004) have measured the packing density of sand as per the Belgian Standard and correlated the packing density so determined with the water demand of the sand in mortar. However, In spite of the good correlation obtained by them, it is, in fact, not appropriate to measure the packing density of sand using any dry packing method (Fung et al. 2008).

1.1 *Theoretical models*

Packing models, which are used to estimate the packing density of the aggregate, have been developed over the past 70 years. The **Furnas** model (Goltermann et al. 1997) considered the ideal packing of spherical particles to obtain the maximum density of a binary system. In a mixture of two kinds of particles, 1 and 2 (diameter $d_1 << d_2$, volume fraction r_1 and r_2, packing density φ_1 and φ_2), there are two limiting cases: 1) $r_1 >> r_2$ and 2) $r_1 << r_2$. In case 1 the packing density of the mixture is:

$$\phi = \frac{1}{\frac{r_1}{\phi_1} + r_2} \tag{1}$$

In case 2 the packing density of the mixture is:

$$\phi = \frac{\phi_2}{r_2} \tag{2}$$

The Furnas model is only valid for a binary system at which $d_1 << d_2$.

Toufar model (Toufar et al. 1976) calculated the packing density of a multi-component mixture (more than 2 classes). The basic concept of the model is that the diameter ratio of smaller particle/larger particle is larger than 0.22, the smaller particle is too large to be situated within the interstices between the larger particle and the mixture forms some packed areas consisting mainly of smaller particles. For three limiting cases of a binary system, 1) $d_1/d_2 \rightarrow \infty$, 2) $d_1/d_2 \rightarrow 0$, and 3) $d_1/d_2 \rightarrow 1$, the function z is defined in table 1.

Table 1. Values for different d_1/d_2 cases in Toufar model (Toufar et al. 1976).

Conditions	Z
$d_1/d_2 \rightarrow \infty$	0
$d_1/d_2 \rightarrow 0$	$r_2[1+\Phi+\Phi_2 / (\Phi_1-\Phi_1 \Phi_2)]2 /[(\Phi_1-\Phi_1\Phi_2)-\Phi_2/(\Phi_1-\Phi_1\Phi_2)]$
$d_1/d_2 \rightarrow 1$	r_2

The packing density is calculated by inserting z value into the equation:

$$\phi = \frac{1}{\frac{r_1}{\phi_1} + r_2 + z \times (\frac{1}{\phi_2} - 1)} \tag{3}$$

Like the Furnas model, **Aim and Goef model** (Goltermann et al. 1997) uses in binary mixture only. Assuming the particles are spherical, the volume fraction of the fine particle r_1^* that gives the maximum packing density is:

$$r_1^* = \frac{1-(1+0.9\frac{d_1}{d_2}) \times (1-\varepsilon_0)}{2-(1+0.9\frac{d_1}{d_2}) \times (1-\varepsilon_0)} \tag{4}$$

If the shape of the fine and coarse particles are not spherical, the r_1^* becomes

$$r_1^* = \frac{\frac{\phi_1}{\phi_2} - (1+0.9\frac{d_1}{d_2}) \times \phi_1}{\frac{\phi_1}{\phi_2} - (1+0.9\frac{d_1}{d_2}) \times \phi_1 + 1} \tag{5}$$

where φ_1 and φ_2 are the experimental packing densities of fine particles and φ_2 is the experimental packing density of coarse particles. In case the volume fraction of fine particles r_1 is smaller than r_1^*, the packing density is:

$$\phi = \frac{\phi_2}{1-r_1} \tag{6}$$

1.2 *Laboratory Methods*

1.2.1 *Dry Packing*

One of the methods applied to calculate the maximum packing density of aggregate is calculated by ASTM C 29 (Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate). This method is used to calculate the bulk density and the voids volume between fine and coarse aggregate in the collection of aggregate uses in compacted conditions and loose conditions. If the measure also is to be used for testing for bulk density of freshly-mixed concrete according to Test Method C 138 (Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete), the measure shall be made of steel or other suitable metal not readily subject to attack by cement paste. The sample that choose for calculating collection packing density must have the volume near 125 to 200 percents of the container volume, and must keep in oven with 110±5 of temperature for one day . This standard calculates the packing density in three ways.

To calculate the voids' volume, it is necessity to know the aggregates specific density that can be use according to the sort of aggregates so that are fine aggregates or coarse aggregates from ASTM C 127 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate) and ASTM C 128 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate). However, calculation of the specific gravity of fine aggregates is tedious and time-consuming in this method.

1.2.2 *Wet Packing*

The majority of available laboratory methods to measure the packing density of aggregates are based on dry conditions. These methods are sensitive to quantity of packing and according to the way of selecting and calculation; the quantity of packing density will be different. Because of the making force between the fine ingredients these methods are not suitable for cement material in dimension of fine ingredients. One of the new laboratory methods, which are recommended recently, is recognized with wet packing (Fung et al. 2008). In this method, the packing density of aggregate calculated by considering the effect of plasticizer and water content and has less sensibility in quantity of packing and can also use in cement ingredients.

According to the consequences of a research (Wong & Kwan 2008), lastly, it is advocated that the dry packing density method should be replaced by the wet packing method for the following reasons. First, the wet condition is more realistic. Second. The wet packing method is less sensitive to compaction; thus should yield more consistent results. Third, if so desired, the effect superplasticizer may be incorporated. Fourth, the beneficial effect of blending is better revealed. Fifth, the wet packing method may be used together with that for cementitious materials to measure the packing density of all the solid particles in mortar and concrete (Fung et al. 2008).

2 EXPERIMENTAL PROGRAMS

Calculating of packing density in aggregates in two methods was mentioned.

For this purpose, five different mixing designs in mortars size was made and calculated the aggregate packing density in compacted conditions and loose compacted conditions. Surveying in sensibility of aggregate packing density in fine size with the laboratory methods is our purpose in this work.

2.1 *Test Methods*

These two laboratory methods are listed in Table 2 briefly.

Table 2. Test Methods.

Laboratory method type	Preambles
Compact Method	Fill the measure one-third full and level the surface with the fingers. Rod the layer of aggregate with 25 strokes of the tamping rod evenly distributed over the surface. Fill the measure two-thirds full and again level and rod as above. Finally, fill the measure to overflowing and rod again in the manner previously mentioned. Level the surface of the aggregate with the fingers or a straightedge in such a way that any slight projections of the larger pieces of the coarse aggregate approximately balance the larger voids in the surface below the top of the measure.
Loose method	In this method the concrete mix poured from 30cm height.
Wet packing	Mixing with water, filling into a container, compaction (if any) and bulk density measurement. First, the aggregate was thoroughly mixed with a predetermined amount of water. Then, the mixture was filled into a container. After filling, compaction was applied to the mixture, if required. Finally, the bulk density of the mixture was measured to evaluate the solid concentration of the particles.

2.2 *Materials and Mixing Designs:*

The Ordinary Type II Portland Cement (OPC) was used in the current work. The Fly Ash was used for simulation of Conditions and SCC mixing design. The used sand had maximum size of 2.36 mm, specific gravity of 2.56, absorption value of 2.7%, was employed in all mixtures. Fig. 1 shows the particle size distribution curve of the using sand.

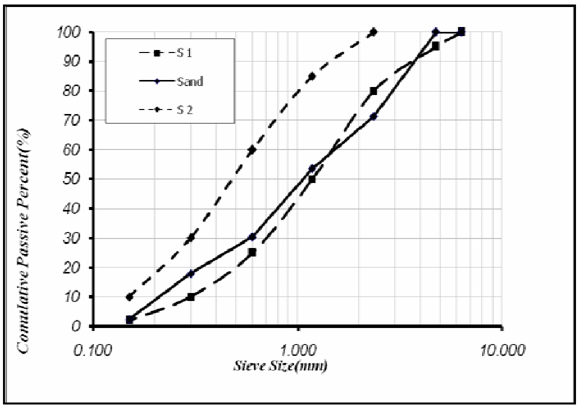

Figure 1. The particle size distribution curve of the using sand. Note: S1 and S2 were derived from the sand grading limits described by ASTM C33.

To simulate the conditions of SCC, a situation has been considered in which the pertained limestone powder was in the mixing design, with specific gravity of 2.8, absorption value of 3.1% and maximum aggregate size of 2.3 mm, was employed in all mixtures. Figure 2 illustrates the particle size distribution curve of this limestone powder.

Five different mixing designs with different combinations weighting proportion used in the current work are listed in Table 3.

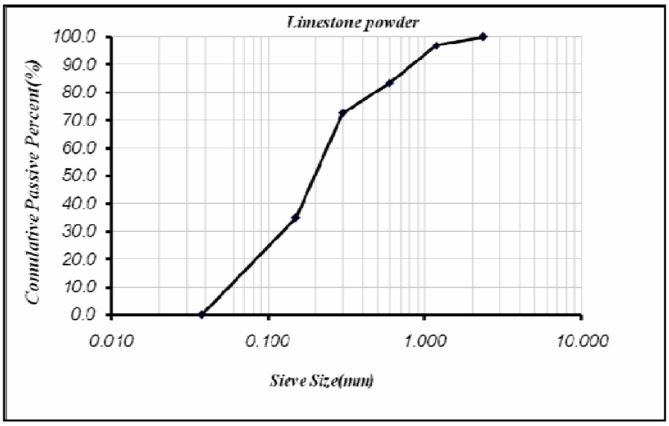

Figure 2. The particle size distribution curve of the using limestone powder.

Table 3. Percentage of mixing design*.

Mix ID	C %	L.P. %	S. %	C / (C+ FA)
MF1	20	10	70	80
MF2	20	20	60	90
MF3	20	25	55	80
MF4	20	30	50	90
MF5	20	20	60	80

* C: Cement, L.P.: Limestone Powder, S.: sand, and C/ (C+FA): Cement/ (Cement + Fly Ash) Ratio

3 RESULTS AND DISCUSSION:

By using ASTM C29 [23], the get packing density in both two method, Compact method and loose method and results of using the Toufar model are listed in Table 4.

Table 4. The packing density of mixtures in three computation situations.

Mix ID	**Specific gravity**	**packing density of aggregate**		**Wet packing method**	**Toufar model**
		Loose method	Compact Method		
MF1	2.55	0.68	0.75	0.72	0.73
MF2	2.55	0.68	0.78	0.75	0.76
MF3	2.55	0.65	0.72	0.70	0.71
MF4	2.55	0.64	0.73	0.72	0.72
MF5	2.55	0.65	0.78	0.76	0.77

Figure 3 calculated numbers has showed the packing density.

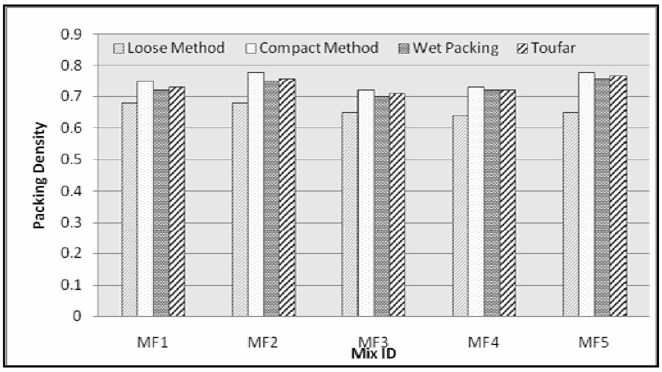

Figure 3. Packing density counted via the two methods.

In the table 5, comparisons between the computed values through the both experimental methods are listed in Table 5. It has been seen that the computed packing densities are different from both method with a difference of 10 up to 20 percent. These differences show the importance when we know that the difference between well-graded and gap-graded is about these limits (extends). The results show the susceptivity of computing of packing density with dry method to compact energy. When this method uses for the fine aggregate, the susceptivity of this method plays an important role in calculating the packing density, this susceptivity result in to the high tolerance. This matter in cementitious materials as it was said is more important because of establishing a Van de Waals force between the particles.

According to Table 5, the counted results from Dry packing method in loose method are from seven to twelve percent less than the Toufar model results. Also in the Compact method the results are from one to three percent less than the Toufar method. The counted results from the wet packing method are from zero to two percent less than the Toufar model results. The less tolerance of the wet packing method results and also being closer to the Toufar model, results shows that it is a more suitable method and has lees susceptivity to the experiment method and is more reliable for the mortar to count experimental packing density.

Table 5. The proportion of counted values among experimental method and Toufar model.

Mix ID	The proportion of Compact method to Loose method	The proportion of Loose method to Toufar results	The proportion of Compact method to Toufar results	The proportion of wet packing to Toufar results
MF1	1.1	0.93	1.03	0.98
MF2	1.15	0.90	1.02	0.98
MF3	1.11	0.91	1.01	0.98
MF4	1.14	0.88	1.01	1
MF5	1.2	0.84	1.01	0.99

4 CONCLUSIONS

The packing density of aggregate was affected in the properties of fresh and hard concrete, and the attentions of researchers to compute this factor shows the importance of it. The measurement and computing methods the packing density are various from the theoretical and experimental methods, and each of these methods has benefits and limitations. To choose the suitable method in theoretical methods should be aware of its theories and limitations. In experimental methods for computing this factor, the experiment operation method and compact energy in computed quantity is very effective.

According to the experimental results, the difference between the counted values through the Compact and loose methods was considerable (from 10 to 20 percent). That means that the compact energy affects the experimental dry method. This susceptivity in smaller scale because of the importance of Van der Waals force between particles would be greater and would give this result that the wet packing method for the small dimensions, because the non-susceptivity of this method is more suitable than the compact energy.

The counted results from Dry packing method in loose conditions are from seven to twelve percent less than the Toufar model results. Also in Compact method the results are from one to three percent less than the Toufar method. The counted results from the wet packing method are from zero to two percent less than the Toufar model results. The less tolerance of the wet packing method results and also being closer to the theoretical method, results shows that it is a more suitable method and has lees susceptivity to the experiment method and is more reliable for the mortar to count experimental packing density.

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