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A REVIEW ON OPTIMIZATION OF CONCRETE USING PACKING DENSITY THEORY

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Abstract— A number of theories have been developed to optimize concrete. Amongst them the optimization of aggregates is advantageous for economical and technical reasons. Packing of an aggregate blend is a measure reflecting how solid part and air voids would share the volume occupied by the blend. It is usually measured in terms of ''packing density". Given a unit volume filled with particles, packing density or packing degree is the volume of solids in this unit volume and is equal to one minus the voids. Lesser the voids lesser will be the requirement for cement paste and thus the defects arising in concrete attributed to cement paste can be mitigated to a certain extent. Packing density is a function of gradation, shape of the particles, texture of aggregate surface, type and amount of compaction effort, aggregate strength, layer thickness. Some general guidelines such as ACI 211 – ASTM C 33, Compressible Packing Model, Shilstone, 18-8 specification, based on field experience, have been developed. One is intended for users of the ACI 211 – ASTM C 33 method who want to optimize aggregate proportions. The other is intended for eventual users of the Compressible Packing Model. CPM is more complex and requires more testing than ACI 211 – ASTM C 33. As a result, it might not be the preferred procedure for some users. ACI 211 - ASTM C 33 is focused on the proportioning and optimization of aggregates. A detailed comparison can be done using different proportioning guidelines for optimization of concrete.

Keywords— Packing Density, Strength, Compressible Packing Model, Aggregate packing.

I. INTRODUCTION

The concept of particle packing has already been applied to the aggregate proportioning for optimum concrete mix design. Early in the 1960s, Powers had suggested that a concrete mix may be considered a mixture of aggregate particles and cement paste. The conceived that paste trapped inside the voids in the bulk volume of aggregate is not effective in lubricating the concrete mix and that only the excess paste (the paste in excess of that needed to fill up the voids) is effective in lubricating the concrete mix. Hence, if the packing density of the aggregate is increased, the amount of paste needed to fill up the voids will be reduced and consequently, for the same amount of paste, there will be more excess paste to improve the workability, or for the same required workability, the amount of paste may be reduced. Based on this excess paste theory, one of the performance criteria for aggregate proportioning has been set as the achievement of a high packing density.

- **PACKING DENSITY (PD)**

Packing Density (PD) is the ratio of solid volume of aggregates to bulk volume of them and can be measured under compacted or uncompacted conditions. PD can be determined under either condition. If it is determined under compacted condition, the method of compaction needs to be mentioned since compaction energy applied in each method is different. PD value can be very close to one if particles in blended aggregates are mixed together such that smaller particles fill the voids created by larger aggregates indefinitely .However, it is somehow unrealistic to achieve a packing density very close to one since there is always a limitation in particle size distribution. In addition to that, the fine particles cannot be too fine and, therefore, there is always voids remained unfilled. Shape of aggregates also plays important role in PD of aggregate blend, specifically particle Shape Factor and Convexity ratio. A low shape factor and/or a low convexity ratio would adversely affect the packing density since they contribute to large aggregate interlocking and higher voids ratio in the blend. According to the literature, the major factors affecting the packing property of blended aggregates are:

i. Gradation (e.g. continuously-graded, gap-graded);
ii. Shape of the particles (e.g. cubical, round and flat and elongated particles);
iii. Texture of aggregate surface (e.g. rough, smooth);
iv. Type and amount of compaction effort;
v. Aggregate strength;
vi. Layer thickness.

II. LITERARURE REVIEW

A. Taher Baghaee Moghaddam, Hassan Baaj, "Appication of compressible packing model for optimization of asphalt concrete mix design", Construction and Building Materials 159 (2018) 530-539, University of Waterloo, Waterloo N2L 3G1, Canada.

In this paper, Compressible Packing Model (CPM) is described as a potential technique to optimize aggregate blend by optimizing the packing density in asphalt mixes. Gradation envelops for high-performance asphalt mixes or Enrobé à Module Élevé (EME) were determined for two different mix types using CPM. There are different methods that have been used for PCC mix proportioning based on PD. One of the methods is Compressible Packing Model (CPM) which was introduced by de Larrard, 1999.

Packing Density (PD) = $\frac{(Solid\ Volume\ of\ Particles)\ (Solid\ Volume\ of\ Particles)}{Bulk\ Volume\ of\ Aggregates Bulk\ Volume\ of\ Aggregates}$

Voids Ratio = 1 – PD

This study investigated the use of CPM in optimization of aggregate packing for high performance asphalt mix. The parameters affecting aggregate packing were discussed in the paper. Five classes of aggregates were used in this study and morphological parameters of fine and midsize aggregates were determined using an aggregate image analyser. CPM model was used to obtain the gradation limits of particles as discussed in this paper and the results were compared with the theoretical maximum density curve used in the Superpave mix design methodology. Based on the results achieved in this study the following conclusions can be derived:

- The comparison showed for 12.5 mm NMAS the gradation curves obtained from CPM and the maximum density curve were very close at some points. However, the two curves were considerably different which could be attributed to the other involved factors such as aggregate shape parameters and limitation of aggregate size distribution in the blend.
- There was a significantly better correlation between the CPM-obtained gradation and the maximum density curve for 19 mm NMAS.
- The CPM-obtained gradation limits were compared with EME 14 and EME 20 limits. It was concluded that the obtained limits were close to the values recommended by European specifications for EME mixes.
- Asphalt mixes were fabricated using the design gradations (mean of upper and lower gradation limits). Compactibility and volumetrics of asphalt mixes were also assessed. It was observed that both mixes had higher workability than the conventional mix, further, Mix B was more workable and had smaller void content compared to mix A which could be associated with higher packing degree of the mix.
- Dynamic modulus test results showed that Mix A had relatively higher stiffness than Mix B when both mixes had the same rich-ness factor.
- Both mixes could meet the minimum requirement of stiffness value, 14,000 MPa at 15 LC and 10 Hz loading, by adjusting the binder content.
- Both mixes had relatively low phase angle and behaved more elastically. Effect of optimized aggregate structure was more evident on the behaviour of asphalt mixes at lower frequency and higher temperatures.

For further research, asphalt mixes will be fabricated using CPM-obtained gradations and the thermo mechanical performance tests will be conducted to evaluate asphalt mix performance in terms of fatigue and permanent deformation resistance.

$\frac{n(n-1)x^2}{2!}$

B. F.de Larrard, T. Sedran, "Optimization of ultra-high performance concrete by the use of a packing model", Cement and Concrete Research, Vol. 24, No. 6, pp. 997-1009, 1994, Laboratoire Central des Ponts et Chaussees , Paris-France.

This paper presents two models allowing to predict the packing density of a particle mix. These models are derived from the Mooney's suspension viscosity model. At a second step, considerations on the parameter to be maximized during the mix-design process are presented. Reference is made to the Maximum Paste Thickness concept, which leads to choose a fine sand for optimizing the compressive strength of cementitious materials. Then, an optimal material is sought, based on the following requirements: fluid consistency, classical components (i.e. ordinary aggregate, sand, Portland cement, silica fume, superplasticizer, water), and moderate thermal curing.

Thus, the matrix final porosity π_M can be evaluated by the following formula:

$\pi_M = (0.23\ V_w + V_a)/(1 - g)$.

Thus, the matrix final porosity π_M can be evaluated by the following formula:

$E_M = D(3\sqrt{g^*/g}-1)$

N°	η_r	Sand type	Silica fume (%)*	Cement (%)*	Sand (kg)	Cement (kg)	Silica fume (kg)	Water (kg)	W/C	S/C	W/(C+S)	Air (%)	MPT (mm)	MFP	Rc (MPa)
1	10000	s400	16.0	51.5	724.9	1148.6	356.9	199.6	0.174	0.311	0.133	2.7	0.088	0.100	232.7
2	10000	s250	16.2	52.5	697.4	1167.9	359.3	202.7	0.174	0.308	0.133	2.5	0.079	0.097	229.0
3	10000	s125	18.0	57.9	526.9	1265.8	393.5	220.5	0.174	0.311	0.133	3	0.046	0.100	223.6
4	10000	s400	15.0	48.5	813.2	1080.6	334.2	198.2	0.183	0.309	0.140	2.6	0.075	0.103	237.9
5	20000	s400	15.0	48.5	824.5	1095.6	338.9	187.0	0.171	0.309	0.130	4.6	0.073	0.129	214.5
6	40000	s400	15.0	48.5	834.8	1109.3	343.1	176.9	0.159	0.309	0.122	4.7	0.072	0.127	221.1
7	80000	s400	15.0	48.5	842.9	1120.1	346.4	168.9	0.151	0.309	0.115	5.8	0.071	0.141	229.0
8	100000	s400	15.0	48.5	845.3	1123.3	347.4	166.5	0.148	0.309	0.113	5.7	0.070	0.139	224.0
9	40000	s400	18.0	60.0	502.4	1370.2	411.1	188.6	0.138	0.300	0.106	6	0.138	0.127	222.9
10	18000	s400	12.1	39.0	1088.3	868.0	269.3	191.3	0.220	0.310	0.168	1.9	0.041	0.106	224.0
11	10000	s400	12.1	39.0	1076.0	858.2	266.3	200.5	0.234	0.310	0.178	2.4	0.043	0.117	216.7
12	5000	-	36.0	64.0	0.0	1339.4	753.4	244.0	0.182	0.562	0.117	5.1	∞	0.107	177.2
13	10000	-	25.0	75.0	0.0	1647.1	549.0	231.1	0.140	0.333	0.105	7	∞	0.123	192.9
14	2000	-	20.0	80.0	0.0	1682.8	420.7	274.5	0.163	0.250	0.130	1.6	∞	0.079	244.9
15	500	-	20.0	80.0	0.0	1601.7	400.4	309.5	0.193	0.250	0.155	1.2	∞	0.083	207.8

Table no. 1 - Composition and properties of the different mixes (series I).

The Solid Suspension Model is a valuable tool to optimize high packing density cementitious materials. Using the equipment available for this study, it allowed to produce a fluid mortar with a 0.14 water-binder ratio. In order to maximize the compressive strength with a set of components, it is first desirable to use only fine sand for aggregate; then a moderate theoretical viscosity is chosen (about 104 the one of water). Finally the Matrix Final Porosity, as predicted by equation $\pi_M = (0.23 V_w + V_a)/(1 - g)$, is taken very low while keeping an aggregate volume sufficient sufficient enough to confine the paste. A simple thermal curing (at normal pressure and humidity) is an efficient way to increase the final compressive strength of ultra-low water-binder ratio mortars. Here, a value of 236 MPa has been achieved with a 4-day curing at 90°C. Thus a new range of 200 MPa-mortars, requiring only a moderate thermal curing, appears to be industrially feasible. Further research is necessary to determine the critical Maximum Paste Thickness under which the influence of this parameter on compressive strength reaches a maximum. Once this value is known, an economical optimization will be possible. Also, many questions concerning this new type of ultra-high-performance mortars are still open, such as temperature rise, shrinkage or brittleness.

C. A.K.H. Kwan, J.J. Chen, "Adding fly ash microsphere to improve packing density, flowability and strength of cement paste", Power Technology 234 (2013) 19-25, The University of Hong Kong, Pokfulam, Hong Kong.

Fly ash microsphere (FAM) is a superfine fly ash. Being finer than cement, it can fill into the voids between cement grains. To study the effects of adding FAM, cement paste samples with FAM contents ranging from 0 to 60% and different water contents were made for packing density, flowability and strength measurements. The results showed that the addition of up to 40% FAM would significantly increase the packing density of the cementitious materials. With the voids partially filled by FAM and the same volume of water in the voids released, the addition of FAM could increase the water film thickness of the cement paste.

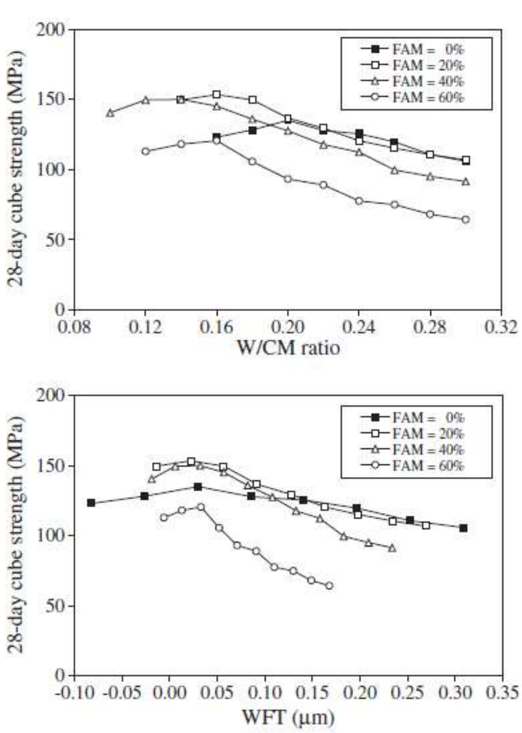

Figure 1 – cube strength versus W/CM ratio and WFT

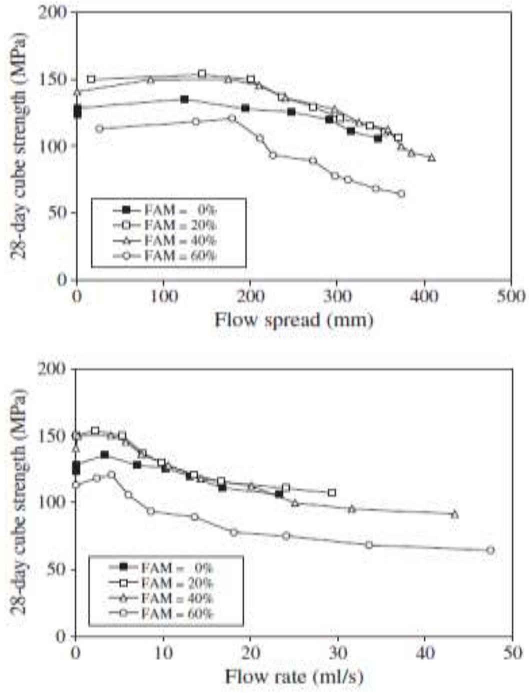

Figure 2 – concurrent cube strength and flowability performance

An experimental program aiming to evaluate the effectiveness of FAM as a cementitious filler for increasing the packing density of cementitious materials and improving the performance of cement paste has been completed. The test results demonstrated that the addition of up to 40% FAM could increase the packing density by 19.7% and decrease the voids ratio by as much as 44.5%. However, due to increase in solid surface area at the same time, the addition of FAM increased the WFT only at relatively low W/CM ratio (≤0.22 for FAM content up to 40% and ≤ 0.24 for FAM content up to 20%). At relatively high W/CM ratio (>0.26 for any FAM content), the addition of FAM decreased the WFT instead. Hence, the addition of FAM to increase the packing density could have different effects on the WFT at different W/CM ratios. This is a fundamental research finding because such observed phenomenon may also occur with the use of other fillers.

The cube strength results revealed that the strength increased as the W/CM ratio decreased and then decreased as the W/CM ratio decreased to beyond a certain optimum value. At a higher FAM content up to 40%, the optimum W/CM ratio was lower and the maximum strength achieved was higher. Hence, by adding FAM to increase the packing density, the W/CM ratio could be lowered to increase the strength. For instance, by adding 20% FAM and lowering the W/CM ratio to 0.16, the strength could be increased by 13.6%. Furthermore, study on the effect of WFT revealed that regardless of the FAM content, the optimum WFT for maximum strength was almost constant at 0.03 μm. This value is the minimum WFT to be provided to avoid incomplete filling of the voids with water.

Finally, study on the concurrent strength flowability performance revealed that the addition of up to 40% FAM could increase the strength at the same flowability, increase the flowability at the same strength, or increase both the strength and flowability at the same time. Hence, FAM is an excellent cementitious filler for improving the flowability and strength of cement paste.

D. L.G. Li, A.K.H. Kwan, "Packing density of concrete mix under dry and wet conditions", Power Technology 253 (2014) 514-521, The University of Hong Kong, Hong Kong, China.

In this studies by the authors, a wet packing method has been developed and the packing densities of cementitious materials, fine aggregate and blended fine plus coarse aggregate were found to be higher under wet condition than dry condition. In this study, both the dry and wet packing methods were applied to concrete mixes containing cementitious materials, fine aggregate and coarse aggregate. It was found that for the entire particle system in a concrete mix, the packing density is higher, the voids ratio is smaller and the filling effects of ultrafine supplementary cementitious materials are better revealed under wet condition than dry condition. Therefore, when measuring the packing density of a concrete mix, the wet packing method should always be used.

The wet packing method proposed by the authors has been further developed to measure the packing density of concrete mix under wet condition. Basically, this method mixes all the solid ingredients with water and SP (if any), measures the solid concentration of the water– solid mixture formed at varying water/solid ratio and determines the wet packing density as the maximum solid concentration so achieved. As an important part of the development process, the wet packing method has been compared to the dry packing method by applying both methods to concrete mix samples with different mix proportions and with or without compaction applied.

The test results revealed that water, compaction and SP all have significant effects on the particle packing of concrete mix. In terms of the variation in voids ratio, the effects of various parameters on particle packing are summarized as follows. First, the presence of water could decrease the voids ratio by as much as 46%. Second, the compaction by tamping could decrease the voids ratio by 36% under dry condition and 17% under wet condition, indicating that dry packing is more sensitive to compaction than wet packing. Third, under wet condition, the compaction by vibration could decrease the voids ratio by 27%, showing that vibration is more effective than tamping for compaction. Fourth, the addition of SP could decrease the voids ratio by up to 39%. Both the higher effectiveness of vibration than tamping and the effect of SP could not have been revealed using the dry packing method. Lastly, the voids ratio would initially decrease as the cement content increases and then after reaching a cement content by volume of about 15% to 20%, turn to increase as the cement content further increases. Hence, there is an optimum cement content for minimizing the voids ratio (or maximizing the packing density).

On the other hand, the test results of concrete mixes containing blended cementitious materials revealed that the full potential of blending for packing improvement is better revealed by testing under the wet condition with SP added. Under such condition, blending of OPC with20% PFA could decrease the voids ratio by 13% and 14% at cementitious materials content of 15% and 20%, respectively, blending of OPC with 20% CSF could decrease the voids ratio by 11% and 13% at cementitious materials content of 15% and 20%, respectively, and blending of OPC with 20% PFA and 5% CSF could decrease the voids ratio by 16% and 19% at cementitious materials contents of 15% and 20%, respectively. However, the packing improvement due to blending with CSF, which should have a better filling effect than PFA, is smaller than expected. In future studies, it is recommended to set the SP dosage according to surface area and apply compaction in order to explore the full potential of blending with CSF.

Finally, it is advocated that the conventional dry packing method should be replaced by the wet packing method for the following reasons. First, the wet condition is more realistic because fresh concrete is actually wet. Second, if so desired, the effect of SP can be incorporated. Third, the effect of vibration can be simulated. Fourth, the beneficial effect of blending is better revealed.

III. CONCLUSION

A number of methods are available to gauge the packing density of a concrete mix. Following are the conclusions that can be made after perusal of all the methods. Solid suspension model and compressible packing model have also been developed to optimize the concrete mix to varying degree of success. The packing density of fine aggregate is significantly higher and less sensitive to compaction under wet condition than under dry condition. The effectiveness of FAM as a cementitious filler for increasing the packing density of cementitious materials and improving the performance of cement paste has been completed. The test results demonstrated that the addition of up to 40% FAM could increase the packing density by 19.7% and decrease the voids ratio by as much as 44.5%. It is advocated that the conventional dry packing method should be replaced by the wet packing method for the following reasons. First, the wet condition is more realistic because fresh concrete is actually wet. Second, if so desired, the effect of SP can be incorporated. Third, the effect of vibration can be simulated. Fourth, the beneficial effect of blending is better revealed.

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