Packing Density: A Key Concept for Mix Design of High Performance Concrete

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Abstract: High performance concrete (HPC) has become more and more popular in recent years. However, the various required performance attributes of HPC, including strength, workability, dimensional stability and durability, often impose contradictory requirements on the mix parameters to be adopted, thereby rendering the concrete mix design a very difficult task. The conventional mix design methods are no longer capable of meeting the stringent multiple requirements of HPC. This paper introduces the concept of packing density as a fundamental principle for designing HPC mixes. The concept is based on the belief that the performance of a concrete mix can be optimised by maximising the packing densities of the aggregate particles and the cementitious materials. A preliminary HPC design method, called three-tier system design, is also presented in this paper.

1. Introduction

The grade of concrete is normally defined in terms of its characteristic strength. For this reason, strength has been taken as the most important performance attribute of concrete and research in concrete technology has been focusing on achieving higher strength in the last century. After decades of development, the production of high strength concrete (HSC) up to grade 100 no longer presents any major difficulties (Kwan *et al.* 1995a; MacArthur *et al.* 1996). In fact, since further increase in concrete strength would be limited by the strength of the rock aggregate used and could drastically reduce the ductility of the concrete (Kwan *et al* 1995b), it is not advisable to specify any higher strength concrete than grade 100. On the other hand, the production of HSC generally requires the use of a low water/cementitious materials ratio and a high cementitious materials content. The use of a low water/cementitious ratio would decrease the workability of the concrete mix, while the use of a high cementitious materials content would increase the thermal expansion/contraction during strength development and the drying shrinkage in the longer term, i.e. would decrease the dimensional stability of the concrete. Hence, a HSC tends to have a lower workability and a lower dimensional stability. Taking these attributes into consideration, a HSC is not necessarily a HPC.

Nowadays, engineers are demanding HPC that have not only high strength but also all round high performance in terms of other attributes such as workability, dimensional stability and durability. Because of the conflicting requirements of these performance attribute (e.g. increase in strength often leads to decrease in workability and increases in both strength and workability may have to be achieved at the expense of lower dimensional stability etc), HPC is much more difficult to produce than HSC. High dosages of chemical and mineral admixtures may have to be added and mix optimisation is needed in order to achieve all the desired properties. The conventional mix design methods are not capable of coping with such complexities and therefore a new mix design method is necessary for making HPC. 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, is introduced. This concept is playing a more and more important role in modern concrete mix design because of the increasing awareness that maximisation 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, can improve the overall performance of the concrete mix. A preliminary mix design method called "three-tier system design" based on the concept of packing density is also proposed.

2. Packing Density: Theory and Implications on HPC

Imagine a concrete mix composed of a single-sized aggregate and cement paste only. In order to fill up all the gaps between the aggregate particles so as to drive away the air voids in the concrete mix, the volume of cement paste must be larger than the volume of gaps within the aggregate skeleton, Figure 1(a). If, instead of a single-sized aggregate, a multi-sized aggregate is used, the smaller size aggregate particles would fill up the gaps between the larger size aggregate particles, leading to a smaller volume of gaps within the aggregate skeleton, Figure 1(b). This has two implications. Firstly, with a multi-sized aggregate used, the volume of cement paste needed to fill up the gaps within the aggregate skeleton would be reduced. Secondly, if the volume of cement paste is kept the same, the use of a multi-sized aggregate would increase the volume of the excess paste (the portion of paste in excess of that needed to fill up the gaps within the aggregate skeleton), which disperses the aggregate particles, provides a coating of paste for each aggregate particle and renders workability to the concrete mix, Figure

1(c). Hence, the size distribution, or grading, of the aggregate has an important bearing on the paste demand and the workability of a concrete mix.

That the grading of the aggregate can have a great influence on the performance of the concrete mix is actually well known long time ago (Powers 1968). It is only that many parameters (the various size fractions of the aggregate) are needed to describe the grading and the effects of the various parameters are often blurred by the interaction between the various parameters involved. Nevertheless, it is nowadays very clear that the single most important parameter influencing the performance of concrete is the packing density of the aggregate. The packing density of a given aggregate or a given lump of solid particles is the ratio of the volume of solids to the bulk volume of the solid particles. Since the bulk volume is equal to the volume of solids plus the volume of voids, a higher packing density means a smaller volume of voids to be filled and vice versa. Figure 1 illustrates how the concept of packing density can be applied to concrete mix design. In Figure 1(a), the single-sized aggregate can be packed together to occupy only limited space, i.e. can achieve only a relatively low packing density. In Figures 1(b) and 1(c), the multi-sized aggregate can be packed together much more effectively to achieve a much higher packing density. With the paste volume fixed, the increase in packing density of the aggregate could be employed to increase the workability of the concrete at the same water/cementitious ratio or increase the strength of the concrete by reducing the water/cementitious ratio while maintaining the same workability.

Apart from increasing the excess paste at a given paste volume to improve the workability and/or strength of the concrete, the increase in packing density of the aggregate could also be employed to improve the dimensional stability of the concrete. In a concrete mix, it is the cement paste that generates heat of hydration causing thermal expansion/contraction during the early age and shrinks when subjected to drying in the longer term. Hence, the larger the paste volume is, the larger would be the changes in dimension of the hardened concrete due to early thermal expansion/contraction and long term drying shrinkage. The heat of hydration and drying shrinkage of the concrete are dependent also on the water/cementitious ratio, both being larger at higher water/cementitious ratio. The reduction in paste demand due to a higher packing density of the aggregate would for the same workability allow the use of a smaller paste volume at a fixed water/cementitious ratio or a lower water/cementitious ratio at the same paste volume, either of which would significantly improve the dimensional stability of the concrete.

The concept of packing density can be extended to apply also to the cementitious materials, which may include cement and other supplementary cementitious materials, such as pulverized fuel ash (PFA), ground granulated blast-furnace slag (GGBS) and condensed silica fume (CSF) etc. Drawing analogy to the previous case of packing aggregate particles, the packing density of the cementitious materials should have similar effect on the water demand and the flowability of the cement paste. The different types of cementitious materials are generally of different sizes. By mixing appropriate proportions of different cementitious materials together, the medium size particles would fill up the gaps between the larger size particles and the smaller size particles would fill up the gaps between the medium size particles and so forth. Hence, blending cementitious materials of different sizes together could increase the packing density of the cementitious materials and reduce the water demand.

Recent research findings have provided positive support to the above theory. Feng *et al.* (2000) demonstrated that in the presence of a superplasticizer, the addition of GGBS, which has a higher fineness than cement, could improve the fluidity of cement paste through its filling effect. Kwan (2000) found during the development of high strength self-consolidating concrete that at a ratio lower than 0.28, the addition of CSF, which has a mean particle size of about 0.1 μm, could substantially increase the workability of the concrete mix, despite large increase in surface area of the cementitious materials. Such increase in workability may be explained by the ultra-high fineness of the CSF, which allowed the CSF particles to fill up the gaps between the cement grains thereby freeing more mixing water to lubricate the concrete mix. Obla *et al.* (2003) showed that blending cement with an ultra-fine PFA, which has a mean particle size of about 3 μm, would reduce the water demand of the cementitious system, due most probably to the increase in packing density after adding the ultra-fine PFA. More recently, the authors have directly measured the packing density of blended cementitious materials and confirmed that the addition of CSF could significantly increase the packing density of the cementitious system. They have also demonstrated that at a water/cementitious ratio of 0.2, the increase in flowability of the cement paste after addition of CSF could be quite dramatic.

The packing density of the cementitious materials has great impact on the strength of the concrete produced. First of all, the reduction in water demand due to a higher packing density would allow the use of a lower water/cementitious ratio for achieving higher strength. Secondly, better packing would reduce the permeability of the bulk of cementitious materials and thus bleeding of the fresh cement paste. Thirdly, better packing would reduce the porosity of the transition zone by filling up the voids formed as a result of the wall effect of the aggregate with very fine particles. Both the reduced bleeding of the cement paste and the reduced porosity of the transition zone would substantially improve the quality of the transition zone, which, as the weakest link in concrete, has dominant effect on the strength of concrete (Mehta and Aïtcin 1990). This phenomenon is often manifested by having transgranular failure (failure with fracture planes cutting through the aggregate particles) instead of transition zone failure (debonding failure at the transition zone) in high strength concrete made with densely packed cementitious materials containing CSF (Kwan *et al.* 1995b). More recently, Bui *et al.* (2005) have demonstrated that due to improved packing, blending cement with a rice husk ash can lead to an increase in strength of the concrete and that because of the more significant improvement in packing density, the increase in strength is larger when the cement is gap-graded.

Apart from strength, an increase in packing density of the cementitious materials would also improve the overall performance of the concrete. For instance, at the same water/cementitious ratio, the flowability of the cement paste and the workability of the concrete mix would be improved. Furthermore, with increased packing density, the cement paste would be more cohesive and the concrete mix would be less likely to segregate during placing. With the water demand reduced, the water content of the concrete mix might also be adjusted downwards to limit the drying shrinkage (Shacklock and Keene 1957) and improve the dimensional stability of the concrete. Lastly, with better packing, the permeability of the bulk of cementitious materials, both in fresh state and in hardened state, would be dramatically reduced leading to a much higher durability of the concrete (Neville 1995; Lange *et al.* 1997; Obla *et al.* 2003).

Summing up the above discussions, the authors are of the view that the packing density of the solid particles in the concrete mix is the key concept in the design of HPC mixes. Both the packing of the aggregate and the packing of the cementitious materials need to be considered. In fact, it is the grading or packing of the whole range of particles from the coarse aggregate to fine aggregate, to cement grains, and to fine and ultra-fine cementitious materials that determines the overall performance of a concrete mix.

3. Packing of Aggregate

The packing density of an aggregate can be determined directly by measuring the bulk density of the aggregate. The basic procedure is to mix the aggregate particles thoroughly, place them into a container of known volume, and then weigh the aggregate particles in the container. With the solid density of the aggregate particles known, the packing density of the aggregate (the volumetric ratio of the solid in the bulk volume) may be determined simply as the ratio of the bulk density of the aggregate to the solid density of the aggregate particles. The packing density so measured represents how well the aggregate would be packed together. From this, the voids content, i.e. the volume of voids in the bulk volume of aggregate to be filled up with cement paste, may also be determined (the volume of voids as a ratio of the bulk volume is equal to 1.0 minus the packing density). In fact, the British Standard BS812: Part 2 has provided a standard test method for measuring the bulk density of an aggregate under dry condition, based on which the packing density and voids content of the aggregate may be evaluated. The packing density of an aggregate may be measured under compacted or uncompacted condition. As the packing density is dependent on the compaction applied, it should be explicitly stated whether the packing density being referred to is the compacted or uncompacted one.

Imagine that particles of decreasing sizes are mixed together such that the gaps between the particles are filled up successively by smaller size particles. If the filling up process is extended infinitely by incorporating particles of extremely fine size, all the voids can be filled up by solid particles, leading to a packing density very close to 1. However, in reality, this can never be achieved due to several reasons. Firstly, since the finest size particles cannot be too fine and the largest size particles cannot be too large, there is a practical limit to the size range of the particles and therefore there is always some voids remaining unfilled. Secondly, the shape of the aggregate particles has a limiting effect on the packing of the aggregate. It has been found that the major shape parameters affecting the packing density are the shape factor and convexity ratio of the aggregates particles (Kwan and Mora 2001). The shape factor is defined as the mean value of the (thickness×length)/(breadth^2) ratios of the particles, while the convexity ratio is defined as the mean value of the (solid area)/convex area) ratios of the particles, as illustrated in Figure 2. A low shape factor and/or a low convexity ratio would adversely affect the packing density, due to the relatively large interlocking action of the particles, which prevents the particles from positioning themselves at the optimum locations or orientations, as shown in Figure 3.

Thirdly, the surface roughness of the aggregate particles would limit the effectiveness of the mixing and compaction processes. A high surface roughness of the aggregate particles would induce large inter-particle frictional forces during mixing and compaction, and thus reduce the packing density of the aggregate. Lastly, the filling effect of the fine particles is often hindered by two types of particle interactions: the wall effect and the loosening effect (De Larrard 1999), as depicted in Figure 4. The wall effect occurs when the fine particles are butting into the surfaces of very large size particles. Because of such wall effect, the gaps between the fine particles and the surfaces of the very large size particles are prevented from being filled up. This phenomenon is called wall effect because such effect also occurs at the surfaces of the container walls. On the other hand, the loosening effect occurs when the fine particles cannot fit themselves perfectly into the gaps of the larger size particles. As a result, the larger size particles are pushed apart causing the skeleton of the larger size particles to dilate and leading to increase in voids volume or decrease in packing density. Both the wall and loosening effects are depended on the size ratios of the particles interacting with each other and the volumetric proportions of the different size particles. This implies that the grading of the aggregate is a controlling factor of these two effects.

From the above, it is evident that the major factors affecting the packing density of an aggregate include: size range, grading, particle shape, surface roughness, and effectiveness of the mixing and compaction processes. Taking into account the particle interactions, Dewar (1999) has derived a packing model for predicting the packing density of multi-sized aggregate from the grading of the aggregate. De Larrard (1999) has also constructed a packing model called "compressible packing model". In addition to the particle interactions, this model considers also the effect of compaction on the packing density of aggregate. By measuring the packing densities of different types of aggregate and correlating the packing density results to the shape parameters of the aggregate particles measured by digital image processing, Kwan and Mora (2001) have established a packing model for predicting the packing density of single-sized aggregate from the shape factor and convexity ratio of the aggregate particles. This packing model is so far the only one that explicitly allows for the effects of particle shape. Although it is originally developed for single-size aggregate, it can be applied also to multi-sized aggregate by combining with the other models that take into account the particle interactions due to size variation. All these models are valuable tools for predicting and optimizing the packing density of aggregate in the mix design of HPC.

4. Packing of Cementitious Materials

The packing of the cementitious materials has greater effects than the packing of the aggregate on the performance of the concrete produced and therefore should be considered even more carefully in the mix design. In fact, HPC has nowadays developed to such stage that any further improvement in performance is very difficult to achieve.

Nevertheless, the packing density maximisation of the cementitious materials should provide room for the continuous advancement of HPC. For example, Kwan and Ng (2004) have, by blending different types of cementitious materials together to maximise the packing density of the cementitious materials, produced self-consolidating concrete of grade up to 100. However, recent progress in the prediction and maximisation of the packing density of cementitious materials has slowed down dramatically. There are two main hurdles. Firstly, the packing behaviour of the cementitious materials and that of the aggregate are actually quite different and the usual practice of applying the theoretical models and experimental methods originally developed for aggregate particles to cementitious materials often yield erroneous results. Secondly, it is up to now not yet possible to measure directly the packing density of cementitious materials.

It is a common belief that the packing density of cementitious materials can be determined using the method of measuring the dry bulk density of the particles, which has been successfully applied to aggregate for many years. It has been found, however, that when this method is applied to cementitious materials, the packing density results obtained are often unrealistically low and too sensitive to the type and level of compaction applied. The most probably cause was the presence of electrostatic and van der Waals forces at the particle surfaces, which caused flocculation and thus loose packing of the fine particles (Yu *et al.* 2003). Hence, such dry packing method of packing dry particles together for direct measurement of packing density is not really applicable to cementitious materials.

Actually, in a concrete mix, the cementitious materials are always mixed with water to form a cement paste and therefore should be wet. Hence, the packing density of cementitious materials should be measured under wet instead of dry condition. In fact, because of the wetness, which lubricates the fine particles, and the capillary forces, which holds the fine particles together, the effectiveness of the compaction applied is higher under wet condition (De Larrard 1999). The authors have measured the packing densities of pure cement under both dry and wet conditions and found that the packing density of cement under wet condition is substantially higher than that under dry condition. It is therefore suggested that a wet packing method (measurement of packing density under wet condition) should be used instead of the conventional dry packing method. Apart from water, superplasticizer should also be added when measuring the packing density of cementitious materials. Superplasticizer is an essential component of HPC. It disperses the flocculated particles, improves the packing density and thereby reduces the water demand of the cementitious materials. With superplasticizer added, the packing density measured by the wet packing method would be higher.

After many unsuccessful trials with the dry packing method, the authors have recently turned to the possibility of measuring the packing density of cementitious materials by wet packing. Based on wet packing, the authors have developed a new method for the measurement of the packing density of cementitious materials. The main features of this new method are: (1) the cementitious materials are first added and mixed with water to form a paste before packing density measurement; (2) a saturated dosage of superplasticizer is added to the paste in order to disperse the cementitious materials as uniformly as possible; and (3) the packing density is measured repeatedly at different water/cementitious ratios and the maximum packing density obtained is taken as the packing density of the cementitious materials. This newly developed wet packing method has been successfully applied to measure the packing densities of different mix proportions of cement, PFA and CSF. Within the limit of the available literature in this field of research, this is the first time that the packing density of cementitious materials is directly measured.

Figure 5 displays some of the test results obtained by the above test method. From this figure, it can be seen that blending either PFA or CSF with cement would improve the packing density, with the improvement being more significant in the later case. The packing density can be further improved by blending cement, PFA and CSF together. These test results provide experimental evidence, instead of just postulations, that the blending of different cementitious materials together can result in a higher packing density. Such improvement in packing density is the fundamental and in fact governing factor for the enhanced overall performance of HPC. It is therefore important to be able to measure the packing density of the cementitious materials so that the mix proportions could be adjusted to maximise the packing density of the cementitious materials and optimise the performance of the concrete produced.

In order to incorporate the concept of packing density into the concrete mix design method, it is necessary to establish the relationships between the packing densities of cementitious and aggregate particles and the properties of cement paste and concrete mix. At The University of Hong Kong, researches are being carried out to establish the relationships between the packing density of cementitious materials and the rheology of cement paste. The preliminary results obtained so far show that maximising the packing density of the cementitious materials can increase very substantially the flowability of the cement paste formed, especially at low water/cementitious ratio. Figure 6 shows the flow value of cement paste at different mix proportions and different water/cementitious ratios. It should be noted that in this figure the mix proportions and water/cementitious ratios are all by volume. Also, the flow value is expressed as the increase in spread of the cement paste after the mini slump cone with upper and lower diameters of 60mm and 100mm and a height of 70mm was lifted. Tests are also being planned to correlate the properties of concrete to the packing density of the cementitious materials and the packing density of the aggregate so that hopefully a new generation mix design method for HPC based on the packing theory could be developed.

5. Proposed Method: Three-Tier System Design

Up to now, the development of concrete mixes for the production of HPC is still largely by trial and error. This is because most HPC incorporate several cementitious materials and high dosages of superplasticizer, causing them to fall outside the scope of traditional mix design methods, which were originally developed for ordinary concrete. Moreover, the stringent multiple requirements of HPC render the development of a systematic mix design method for HPC very difficult. Without new thinking, it is unlikely that we could overcome this hurdle and escape from having to develop HPC mixes by blind trial. In 1995, Neville has, in his famous book Properties of Concrete 4th Edition, made the statement that “a generalized systematic approach to the selection of mix proportions of high performance concretes has not yet been developed”. It is sad to say that in this year of 2005, this statement remains valid, despite the much higher popularity of HPC compared to the past. With the increasing use and ever demanding performance requirements of HPC, a comprehensive mix design method for HPC is desperately needed. The above newly developed wet packing method, which enables the packing density of the cementitious materials to be explicitly measured, sheds light on a possible new direction for the development of a mix design method for HPC.

In addition to incorporating the concept of packing density into the mix design method, the authors are proposing a “three-tier system” for the mix design of HPC. The central idea of this three-tier system is to categorize the concrete mix into three tiers, each of increasing particle size range, as depicted below:

<u>Cement paste</u>: cementitious materials + water + any superplasticizer added.
<u>Mortar</u>: cement paste + aggregate particles smaller than 1.2 mm.
<u>Concrete mix</u>: mortar + aggregate particles larger than 1.2 mm.

Unlike the conventional two-tier system that categorizes the concrete mix into only cement paste and concrete mix (in the two-tier system, concrete mix = cement paste + aggregate), the proposed three-tier system has one additional tier – the mortar. During mixing and placing of concrete mixes, the authors have observed that even when the concrete mix is showing serious signs of segregation, the aggregate particles smaller than 1.2 mm tend to stay with the cement paste. Hence, it is believed that the aggregate particles smaller than 1.2 mm behave in a very different manner from the larger size particles and that the coherent mixture of cement paste and aggregate particles smaller than 1.2 mm, i.e. the mortar so formed, should have significant influence on the properties of the concrete mix. It is also hoped that the finer division into three tiers would for given materials allow a more optimum mix design to be produced.

The mix design would be divided into three stages. At the first stage, the first tier of materials would be considered. Basically, the packing density of the cementitious materials would determine the water demand, and the excess water should be the dominant factor affecting the rheology and cohesiveness of the cement paste. At the second stage, the second tier would be considered. The packing density of the aggregate particles smaller than 1.2 mm would determine the paste demand, and the excess paste should be the dominant factor affecting the flowability of the mortar. At the third stage, the third tier would be considered. The packing density of the aggregate particles larger than 1.2 mm would determine the mortar demand, and the excess mortar should be the dominant factor affecting the workability of the concrete mix. By correlating the properties of the cement paste, mortar and concrete mix to the packing densities of the cementitious materials, the aggregate particles smaller than 1.2 mm and the aggregate particles larger than 1.2 mm, it should be possible to predict the performance of the concrete produced and optimise the mix proportions for best overall performance.

6. Concluding Remarks

In this paper, the concept of packing density has been introduced. It is believed that maximisation of the packing density of the cementitious materials and the packing density of the aggregate particles could improve the overall performance of the resulting concrete mix and thus should be the general guideline for mix optimisation. On the other hand, despite the increasing popularity of HPC, a systematic mix design method for HPC is still lacking. Nevertheless, the proposed three-tier system design method points to a new direction for the development of a mix design method that is applicable not only to HPC but also to ordinary concrete. The proposed method optimises the concrete mix in three stages, first focusing on the cement paste, then on the mortar and finally on the concrete mix. At each stage, packing density maximisation is carried out. Research studies by the authors on the packing of cementitious materials have already produced some promising results but further studies are needed before all the details of the mix design method could be worked out.

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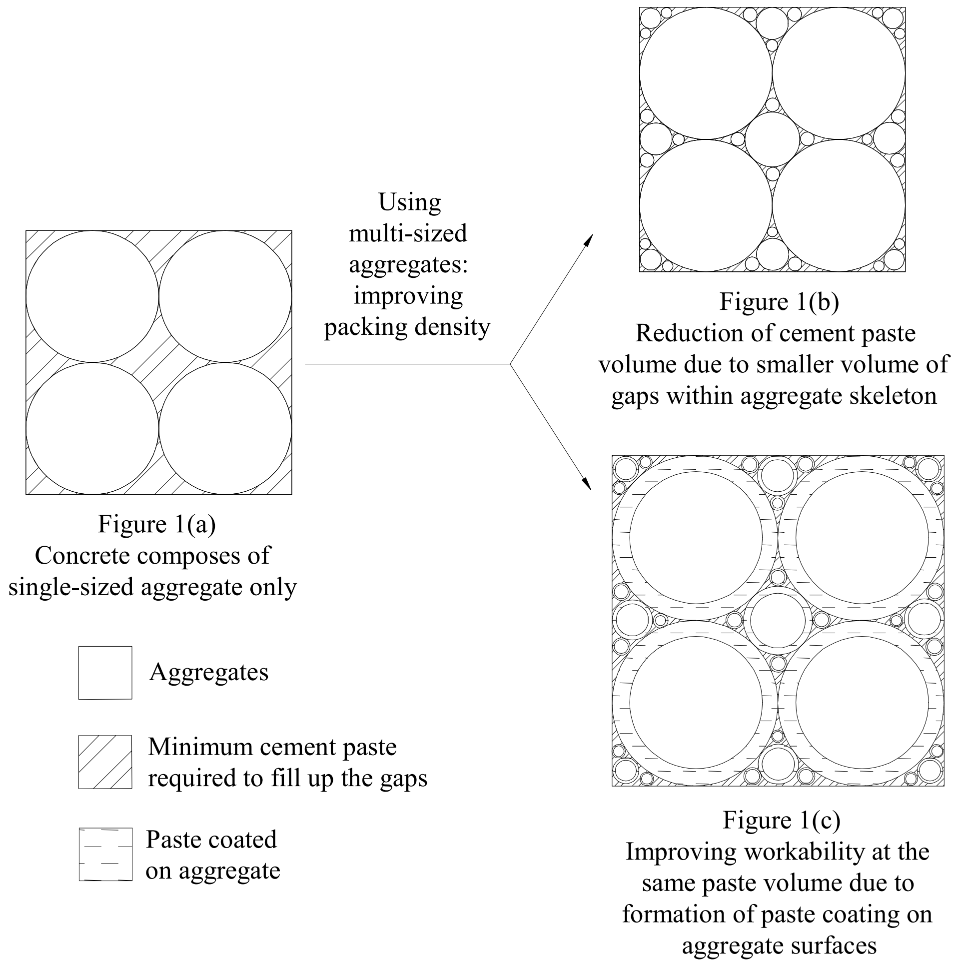

Figure 1 Packing of aggregates

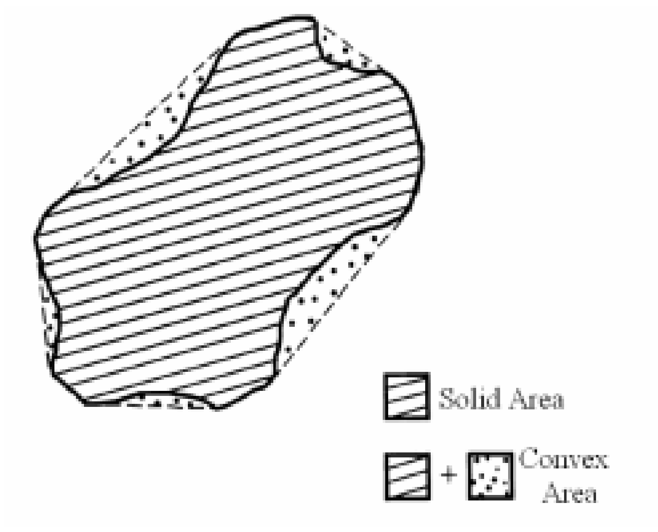

Figure 2 Definition of solid area and convex area (Kwan and Mora 2001)

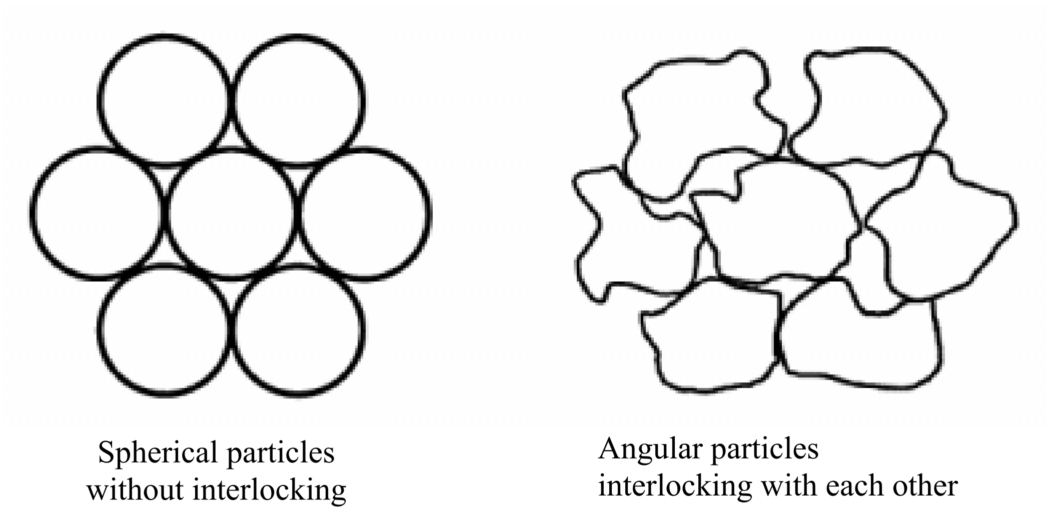

Figure 3 Effect of interlocking action on packing of particles.
(Kwan and Mora 2001)

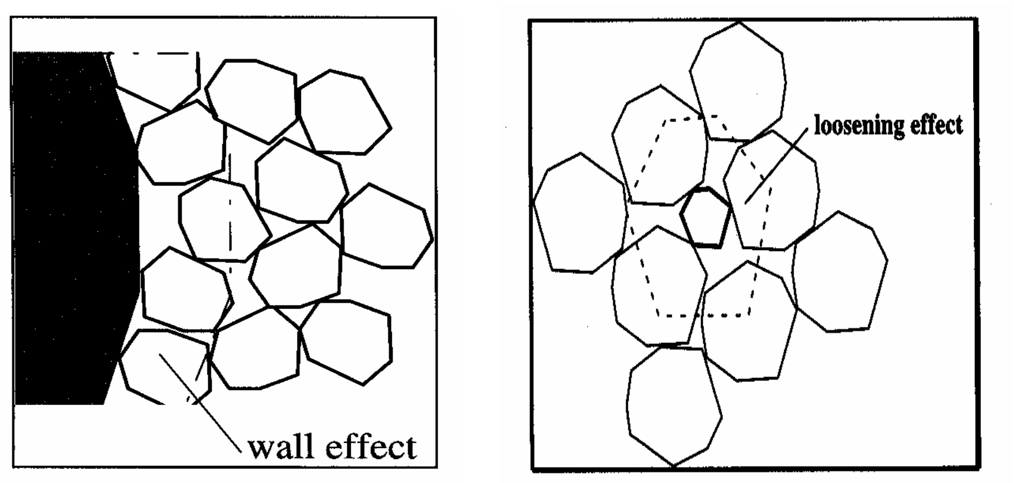

Figure 4 Wall effect and loosening effect (De Larrard 1999)

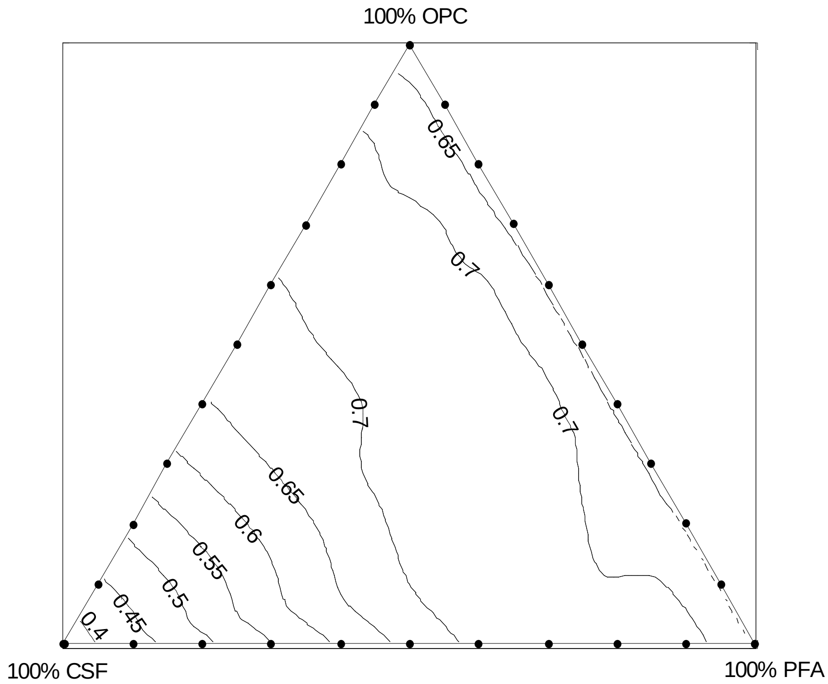

Figure 5 Contour showing the packing densities of cementitious materials at different mix proportions

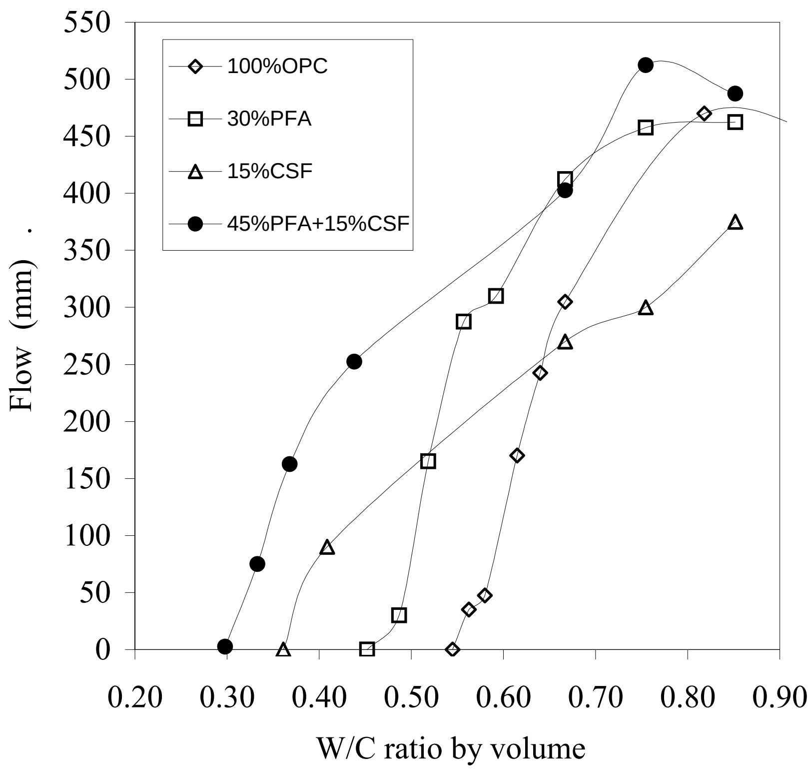

Figure 6 Flow value of cement paste at different mix proportions and water/cementitious ratios