RESEARCH DIRECTIONS FOR HIGH-PERFORMANCE CONCRETE

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Abstract: The continuous development of civil infrastructure has been imposing more and more stringent requirements on the concrete to be used. To meet with stringent requirements, the notion of high-performance concrete (HPC) processing high strength, high workability, high durability and high dimensional stability had been put forward in the last century. After about 20 years of development, a large variety of HPC has been produced. However, since the various performance attributes of HPC are often contradictory to each other and thus difficult to achieve simultaneously, the development of HPC has come to a bottle neck. To cope with such situation, a more scientific approach is needed. Here, we shall explain how conventional concrete technology could be reformed into modern concrete science by incorporating new theories on particle packing, water film thickness and particle interaction. We shall also introduce new technologies such as aggregate treatment, fillers and green concrete. It is our belief that with further advancement in concrete science and technology, even better HPC could be produced for more sustainable construction.

Keywords: high-performance concrete; packing; particuology; sustainability.

1. Introduction

Concrete is the most widely used construction material on earth. Over the years, it has been used in vast quantities for the construction of buildings, bridges, roads, dams and many other civil infrastructures. According to Glavind and Munch-Petersen (2002), its worldwide annual consumption in 2002 was about 5 billion m^3. Moreover, Mehta (2001) predicted that its demand would double every decade. Hence, its performance and effects on the environment are of great importance.

Although all concretes, whether old or new, look very much the same to a layman, concrete as a whole has evolved to such an extent that it is now totally different. More than 50 years ago (before the 1960s'), the concretes produced were mostly 1:2:4 and 1:1:2 nominal mixes with cube strengths of 15 to 25 MPa. The water content was not specified, albeit the water/cement ratio was known to be the major factor governing the strength. There was no plasticizer or superplasticizer that could improve the workability or reduce the water demand so that the water/cement ratio could be reduced to improve the strength.

In the 1960s', plasticizers produced in the form of lignosulphonic acids emerged. Later, in the 1970s', melamine- and naphthalene-based plasticizers were developed. Being more effective, they are called superplasticizers (SPs). Then, more recently, polycarboxylate-based SPs made of synthetic molecules have also been developed. Initially, the plasticizers and SPs were used mainly to reduce the water demand so that a lower water/cement ratio could be adopted to increase the strength of concrete. That is why plasticizers and SPs are sometimes called water reducers and high-range water reducers, respectively.

With the advent of SPs, the production of high-strength concrete (HSC) with characteristic cube strength ≥ 60 MPa began in the 1980s'. However, it was soon realized that the early HSCs were far from ideal. Firstly, the high cement content and large paste volume often led to large thermal expansion/contraction at the early age and large drying shrinkage at the later age. Hence, the dimensional stability of the early HSCs was not really satisfactory. Secondly, since HSCs tend to be more cohesive, they need to be provided with a higher workability for proper compaction and an even higher workability for pumping. The early HSCs were produced with only normal workability. Hence, they were generally difficult to compact and not suitable for pumping. Thirdly, based on the general belief that a higher strength concrete produced with a lower water/cement ratio is automatically more durable, no particular attention was paid to improving the durability of concrete (to be more precise, the durability of the reinforced concrete structure cast). In actual fact, the water/cement ratio is just one of the factors affecting durability and the durability of HSCs could be further improved by adding supplementary cementitious materials. In order to achieve all round high performance in the various performance attributes, Cusens (1991) advocated in his presidential address the development of high-performance concrete (HPC).

Since the 1990s', HPC has advanced so dramatically that nowadays a HPC can have a characteristic cube strength equal to or higher than 100 MPa, a workability high enough for pumping up to 300 m, a temperature rise small enough to render cooling unnecessary during curing and a durability good enough for the concrete structure to last 120 years even in marine environment. However, we should not be too complacent with what we have achieved so far. Firstly, the mix design of HPC is still largely by trial mixing, which is tedious, time consuming and much too slow in response to variations in the properties of the ingredients. Secondly, the SPs being used are so effective that a slight over dosage could lead to segregation, bleeding and sedimentation. What we need is not just high performance, but also high robustness in the production of HPC (robustness is the ability of the concrete to maintain performance despite expected or unexpected variations in the properties of the ingredients). Thirdly, and more importantly, the high cement consumption in the production of HPC is not environmentally friendly. The society is now advocating sustainable development of our civil infrastructure. The production of cement generates a substantial amount of CO_2, which contributes to a fairly large carbon footprint. Hence, it is about time to think about the development of not just HPC, but also green concrete with minimum carbon footprint for sustainability.

Furthermore, the various performance attributes of HPC are often contradictory to each other and thus very difficult to achieve simultaneously. Mix optimization is needed to produce a HPC with all round high performance. Due consideration of the robustness of the concrete is also needed so that the required high performance in the various performance attributes can be consistently achieved. Both the mix optimization and robustness design of HPC require in-depth understanding of how the various mix parameters would affect the behaviour of concrete. In this regard, The University of Hong Kong has been working on the development of HPC for more than 20 years. From the research findings, a number of theories have been developed. These theories are now transforming the conventional concrete technology into modern concrete science, as reported herein.

2. Packing of Solid Particles

At the macro-scale, a concrete mix may be considered to comprise of aggregate particles and cement paste. In the aggregate, there are solid particles of various sizes ranging from 75 μm to the maximum size of aggregate (may be 10, 20 or 40 mm). The medium size particles fill the voids between the larger size particles whereas the smaller size particles fill the voids between the medium size particles. Successive filling of the voids by smaller size particles can decrease the volume of voids and increase the packing density of the aggregate. Since the cement paste has to first fill up the voids in the bulk volume of the aggregate and it is the excess cement paste (cement paste in excess of that needed to fill the voids) that lubricates the concrete mix, a higher packing density would for a given volume of cement paste, improve the workability and for a given workability requirement, reduce the volume of cement paste needed. This packing theory, illustrated by Figure 1, was developed by Powers (1968) in the 1960s'.

At the micro-scale, a cement paste may be considered to comprise of grains of cementitious materials and water. In the cementitious materials, there are solid particles of various sizes ranging from < 1 μm to about 75 μm. As for the case of aggregate at the macro-scale, successive filling of the voids by smaller size particles can decrease the volume of voids and increase the packing density of the cementitious materials. Since the water has to first fill up the voids in the bulk volume of the cementitious materials and it is the excess water (water in excess of that needed to fill the voids) that lubricates the cement paste, a higher packing density would for a given volume of water, improve the flowability and for a given flowability requirement, reduce the volume of water needed. This packing theory may be regarded as an extension of Powers' theory to the micro-scale. However, whilst the packing density of aggregate can be measured under dry condition, due to agglomeration, all early attempts to measure the packing density of cementitious materials under dry condition failed. Without a reliable method for measuring the packing density of cementitious materials, the packing theory for cementitious materials has remained just a postulation.

To overcome the above difficulty, The University of Hong Kong has recently developed a wet packing test for measuring the packing density of cementitious materials under wet condition (Wong and Kwan 2008a; Kwan and Wong 2008a). In fact, since the cementitious materials are mixed with water in the cement paste, it should be more appropriate to measure the wet packing density than the dry packing density. Basically, this test mixes the cementitious materials with different amounts of water and determines the highest solid concentration achieved as the packing density of the cementitious materials. Any air trapped inside the cement paste is taken into account in the calculation of the packing density. If there is SP added to the cement paste, the effect of SP is also taken into account by adding exactly the same dosage of SP into the mixture. The accuracy of the wet packing test has been verified by checking against established packing models and the results indicated that the differences between theoretical results by packing models and experimental results by the wet packing test are well within 3% (Wong and Kwan 2008b; Kwan and Fung 2009).

Using the newly developed wet packing test, the effect of blending cement with various supplementary cementitious materials on the packing density has been studied (Wong, Ng, Ng and Kwan 2007). Basically, the addition of ultrafine particles such as CSF to fill the voids between the cement (or cement + PFA + GGBS) grains can increase the packing density of the cementitious materials and thus release more excess water for lubricating the cement paste. In general, the packing density is dependent to a large extent on the size range and distribution of the particles and to a smaller extent on the shape of the particles. If the particle size range and distribution and the particle shape could be optimized to maximize the packing density of the cementitious materials, then the rheology of the cement paste could be improved. This can be done by a trial-and-error process of measuring the packing densities of difference combinations of cementitious materials or more efficiently by computation using a theoretical packing model. Several packing models have been developed and the most famous one is the linear packing model (De Larrard 1999). For such mix optimization of cementitious materials, The University of Hong Kong has developed a computer program, which is capable of evaluating the packing density of the whole particle system in cement paste/mortar/concrete. This computer program has been in use for more than 2 years but is still being refined by calibrating with a growing database of packing density test results.

3. Water Film Thickness

Apart from the packing density, it has been found that the surface area of the particle system also has great effects on the rheology of cement paste/mortar/concrete. Generally, the larger is the surface area, the lower is the flowability of the cement paste/mortar/concrete. This may be explained in terms of the thickness of the water films coating the solid particles, as depicted in Figure 2. For the same amount of excess water, the water film thickness would be smaller when the surface area is larger and vice versa. A smaller water film thickness would lead to a lower flowability whereas a larger water film thickness would lead to a higher flowability. In this regard, research at The University of Hong Kong revealed that the average water film thickness may be evaluated as the excess water to surface area ratio and that this average water film thickness (or just water film thickness for brevity) is the major factor governing the rheology and cohesiveness of cement paste/mortar/concrete (Kwan and Wong 2008b; Wong and Kwan 2008c; Kwan, Fung and Wong 2010). More importantly, the combined effects of water content, packing density and surface area on rheology and cohesiveness, which have been found by previous researchers to be rather complicated, may be evaluated in terms of one single parameter - the water film thickness.

Traditionally, the strategy for optimizing the mix design of cement paste/mortar/concrete is to maximize the packing density of the particle system (De Larrard and Sedran 1994). However, the addition of very fine particles, such as CSF, ultra PFA, ground PFA, superfine GGBS, superfine limestone filler and superfine cement, to fill the voids and increase the packing density would also increase the surface area of the particle system. Since it is actually the water film thickness that governs the rheology, we should be maximizing the water film thickness, not the packing density. In this regard, research at The University of Hong Kong (Fung and Kwan 2010) revealed that as very fine particles such as CSF particles are added, the water film thickness may increase or decrease, depending on the water content of the cement paste or mortar, as illustrated in Figure 3. When the water content is low, the increase in excess water due to the filling effect of the CSF would be relatively more significant than the increase in surface area and thus the water film thickness would increase as the CSF content increases. On the other hand, when the water content is high, the increase in excess water due to the filling effect of the CSF would be relatively less significant than the increase in surface area and thus the water film thickness would decrease as the CSF content increases.

To allow for mix optimization based on maximum water film thickness rather than maximum packing density, the computer program developed by The University of Hong Kong has been upgraded to evaluate the water film thickness of cement paste/mortar/ concrete. Moreover, an iterative process of successively adjusting the particle size distribution to maximize the water film thickness has been implemented. This upgraded computer program is still being trial run for validation before final release.

4. Particle Interaction

As a water-solid mixture flows, the solid particles contained therein collide and interact with each other, especially when passing through narrow gaps. Due to shearing of different layers of the water-solid mixture, the solid particles in one layer, after colliding at inclined angles with those in adjacent layers, are deflected laterally, thereby causing erratic dilation of the flowing stream of water-solid mixture. As a result, the shear stress needed to maintain continuous flow increases and at the entrance to narrow gaps, the solid particles might pile up causing blockage of the solid particles at the entrance. Hence, the particle interaction in the water-solid mixture could significantly reduce the flowability of the mixture and the passing ability of the mixture through narrow gaps.

Research at The University of Hong Kong revealed that the particle interaction causing reduction in the passing ability of a particle system through a narrow gap is dependent on the particle size to gap width ratio, as shown in Figure 4. The larger is the particle size to gap width ratio, the larger is the particle interaction and the lower is the passing ability of the particle system. Nevertheless, when the particle size to gap width ratio is smaller than 0.2, the effect of the particle size to gap width ratio becomes negligibly small. In general, the particle interaction between finer particles has smaller effects and that between coarser particles has larger effects.

More interestingly, it has been found that the addition of finer size particles to the particle system in such a way that the bulk volume of the finer size particles is more than enough to fill up the voids between the coarser size particles, the passing ability of the particle system could be substantially improved, as shown in Figure 5. This may be explained by the phenomenon that the addition of finer size particles to such extent would produce a layer of excess fine (fine particles in excess of the amount that could be filled into the voids between the coarse particles) coating the coarse particles so that the inter-particle distance between the coarse particles would be increased and the particle interaction between the coarse particles would be reduced. Moreover, it is very likely that the excess fine would act as ball bearings to ease the relative movement between the coarse particles. Hence, the addition of fine particles in excess of the amount needed to maximize the packing density could improve the flowability and passing ability of the particle system. Again, it is shown that the maximization of packing density would not necessarily maximize the performance of cement paste/mortar/concrete.

5. Particuology for Concrete Science

The afore-mentioned theories of *packing of solid particles*, *water film thickness* and *particle interaction* fall within the scope of particuology - the science of particle systems. Research on these theories for concrete is still primitive and unknown to most concrete engineers.

However, these theories could transform the conventional concrete technology, which is more know-how oriented, into modern concrete science, which is more know-why oriented. In fact, using the linear packing model, the packing density, water film thickness and excess fine thickness can all be numerically computed from the water content and particle size distribution of the various solid ingredients. The authors are working hard to develop computer software for this purpose. It is our vision that the rheology and cohesiveness of cement paste/mortar/concrete can be better understood and predicted in terms of the packing density, water film thickness and excess fine thickness of the water-solid mixture.

6. Aggregate Treatment

Since the aggregate constitutes about two-third by volume of the concrete, the properties of concrete are highly dependent on those of the aggregate. For example, the shrinkage and permeability of concrete are both dependent on the quality of the aggregate used. However, importing aggregate from a far away place is very costly and usually, due to economic consideration, the local aggregate is used, even though it may not be of high quality. In Hong Kong, it has been found that the shrinkage and permeability of the concrete made with the local granite aggregate are unusually high (Kwan, Au, Wong and Ng 2010). Nevertheless, research at The University of Hong Kong indicated that as an alternative to importing higher quality aggregate from a distant source, the local aggregate may be treated before use to reduce the shrinkage and permeability of the concrete produced. The high shrinkage and high permeability of the local granite aggregate concrete are due to the high porosity of the granite rock from which the aggregate is derived. So at least in theory, if the pores in the granite rock could be filled with water repellent or polymer latex before being used, it should be possible to reduce the effects of the high porosity of the granite aggregate. Figure 6 shows some of the results on the effects of aggregate treatment on concrete shrinkage obtained so far (Kwan, Fung and Wong 2010). Although the aggregate treatment technology is still immature, the results do indicate that the proposed aggregate treatment could reduce the concrete shrinkage by 13%. Research on more effective treatment method and on the reduction of permeability by aggregate treatment is still ongoing.

7. Fillers

Many different types of fillers are commercially available today. Some fillers, such as ultra or ground PFA, superfine GGBS, superfine limestone filler and superfine cement, are finer than cement and their addition to cement paste/mortar/concrete can increase the packing density of the powder content (powder may be defined as particles finer than 75 μm). Since their addition will also increase the surface area of the powder content, the net effect on the rheology of the cement paste/mortar/concrete can be positive or negative, depending on the particle size distribution of the powder content and the dosage of fillers. Nevertheless, their addition will always increase the cohesiveness and thus help to reduce segregation, bleeding and sedimentation. Some other fillers, such as ordinary limestone fillers and ground sand, are coarser than cement but finer than the fine aggregate. Their addition to mortar/concrete can increase the packing density of the aggregate but will also increase the surface area of the aggregate. Hence, the net effect of their addition on the rheology of mortar/concrete can also be positive or negative. Nevertheless, their addition will always increase the cohesiveness by increasing the surface area and increase the passing ability by increasing the amount of excess fine coating the coarse aggregate particles.

However, there are still no general rules for making good use of fillers. It is the authors' belief that the addition of the right type and amount of filler can significantly improve the performance of concrete by increasing the packing density, water film thickness and excess fine thickness. Systematic studies on how fillers affect the packing density, water film thickness and excess fine thickness are needed so that eventually a mix optimization method for the use of fillers can be developed. It is also the authors' belief that the addition of fillers can help to reduce the cement content of the concrete. This will reduce the carbon footprint of the concrete and contribute to sustainable development.

8. Green Concrete

The production of cement, a key ingredient of concrete, involves the heating of limestone, which generates almost one ton of CO_2 for each ton of cement produced. It is estimated that 7-8% of global greenhouse gas emission comes from cement production and the situation is going to become worse because the demand for concrete is predicted to increase substantially in the years to come (Mehta 2001). In order to reduce the carbon footprint of our construction so as to ensure sustainable development, the cement consumption should be minimized. For better identification, concrete which can help to minimize cement consumption is called green concrete.

However, a green concrete is not just a concrete with a low cement content per unit volume. To minimize cement consumption, we should consider not just the cement content per unit volume but also the volume of concrete needed for the structure and the service life of the structure. The use of a higher strength concrete can for the same load capacity significantly reduce the volume of concrete needed for the structure. For the construction of One Island East, a newly completed 70-storey concrete building in Hong Kong, it has been found that the use of Grade 100 concrete instead of the originally planned Grade 45 concrete can reduce the volume of concrete needed for the vertical elements by 30% (Zheng, Chan and Kwan 2009). As the Grade 100 concrete has about the same cement content per unit volume as that of the Grade 45 concrete (the high strength of the Grade 100 concrete was achieved by adding PFA and CSF rather than by increasing the cement content), such reduction in the volume of concrete has significantly reduced the total cement consumption. Furthermore, it has been estimated that the higher durability of the Grade 100 concrete can extend the design service life from 50 years to 75 years or even 100 years. The extended service life will reduce the frequency of future redevelopment and thus reduce the cement consumption per year of service. Hence, a higher performance concrete with both higher strength and higher durability is a greener concrete.

9. Conclusions

With the advent of chemical and mineral admixtures, concrete technology has advanced greatly and many different types of HPC have been developed. However, the conventional concrete technology has remained rather empirical and there are still many aspects of concrete behaviour that are beyond our comprehension. In the past 20 years, The University of Hong Kong has been working on the theories of packing of solid particles, water film thickness and particle interaction, which are evolving into modern concrete science. Based on these theories, computer models and software are being developed for theoretical prediction of concrete performance. It is envisaged that such computer software can help to optimize our mix design for better HPC and allow quicker response during production to variations in quality of the ingredients. Furthermore, The University of Hong Kong is also developing new technologies such as aggregate treatment, fillers and green concrete. Finally, the authors would like to advocate that a HPC is also a green concrete and that we can contribute to sustainability by optimizing the mix design to reduce cement consumption.

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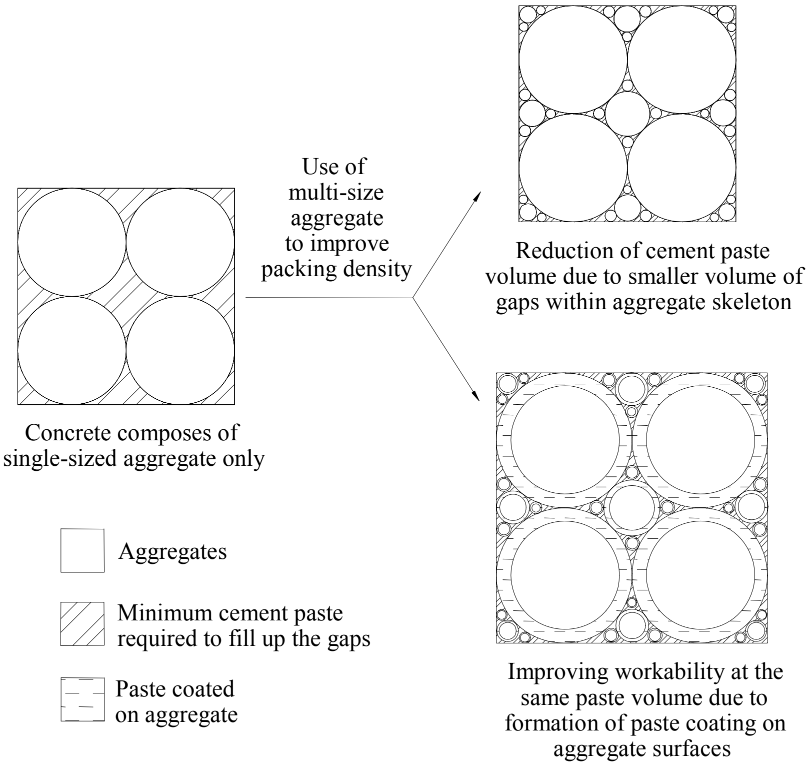


Figure 1 Packing of aggregate

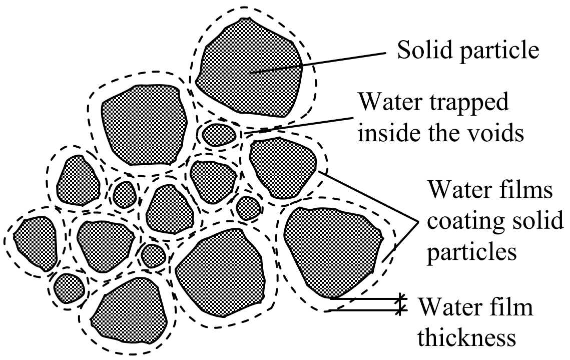


Figure 2 Role of water film thickness

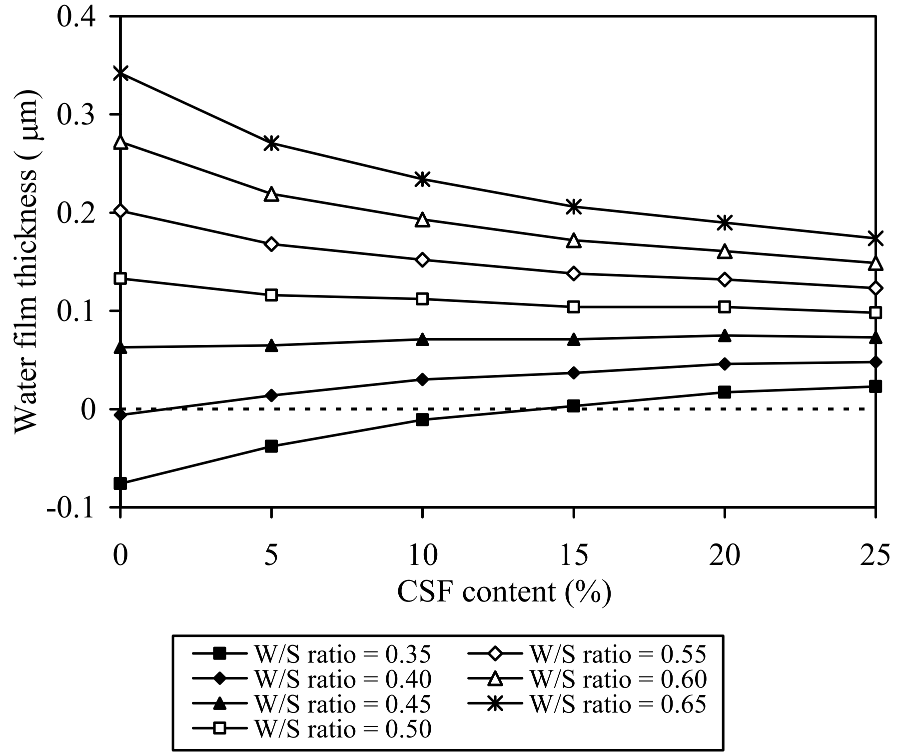


Figure 3 Effect of CSF on water film thickness

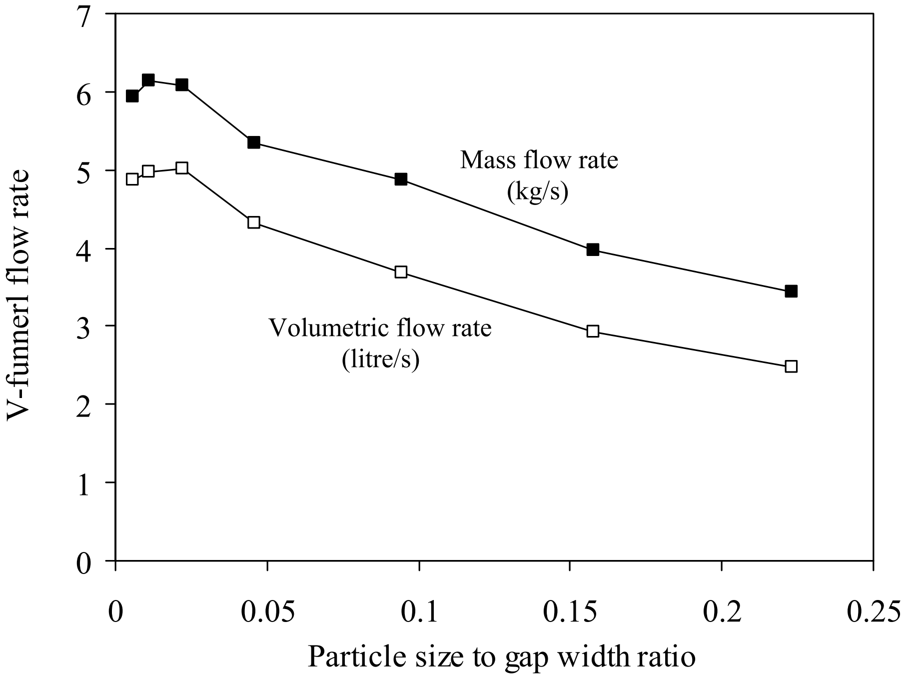
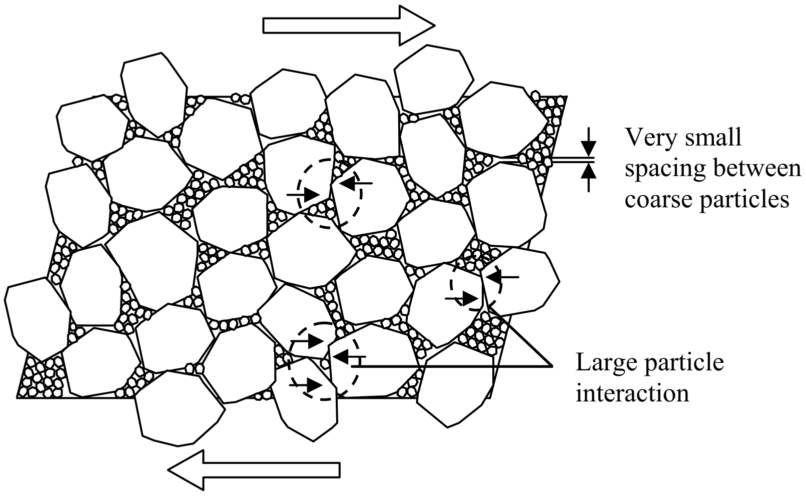
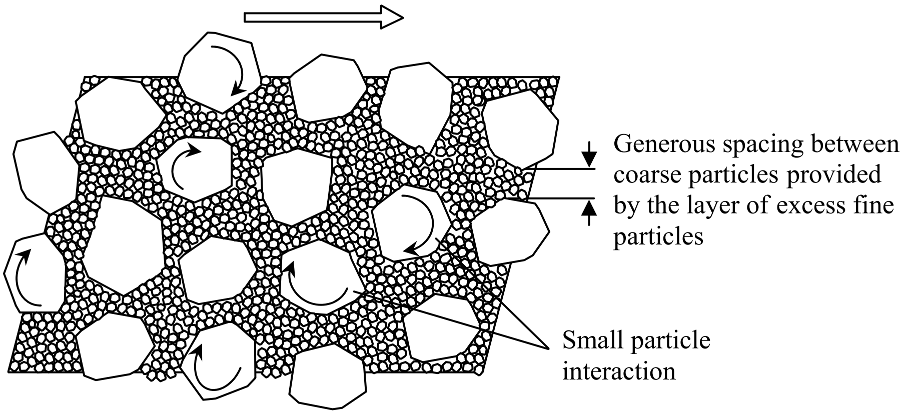


Figure 4 Effect of particle size on flow rate



(a) Large particle interaction



(b) Small particle interaction

Figure 5 Effect of excess fine

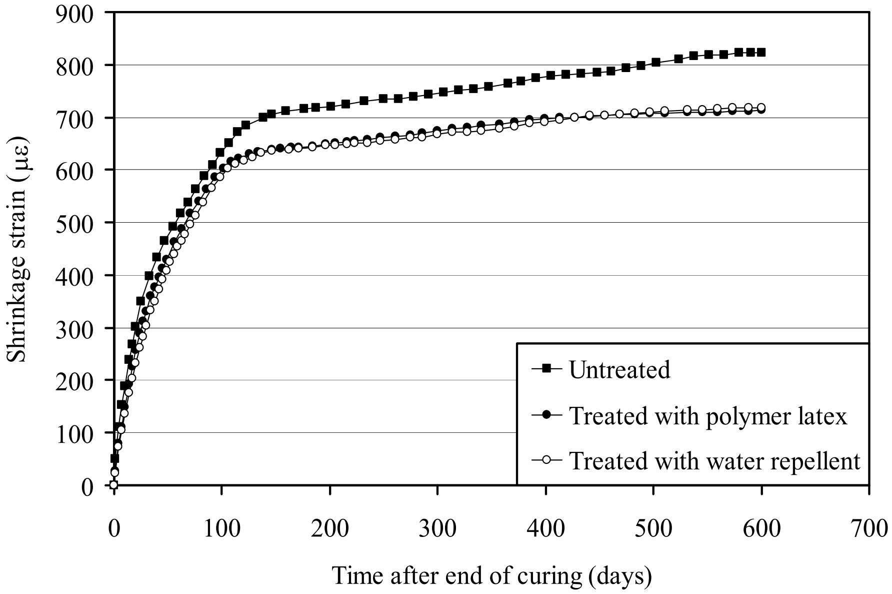


Figure 6 Effects of aggregate treatment on concrete shrinkage