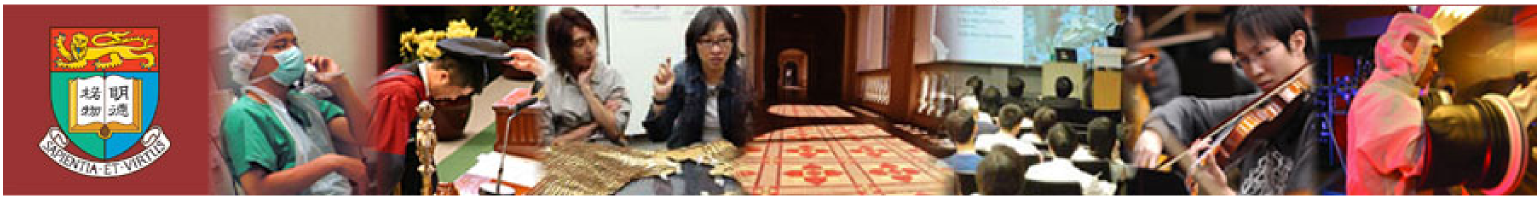

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Reducing drying shrinkage of concrete by treatment of aggregate

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Drying shrinkage of concrete has been found to cause cracking, water leakage and other serviceability problems and is thus an important research topic. In early studies, it has been found that the shrinkage of concrete varies with the rock aggregate used. This is partly because the aggregate also shrinks and the shrinkage of aggregate is dependent on the type of rock from which the aggregate is derived. However, there have been few studies on the shrinkage of rock and how the shrinkage of aggregate would affect the shrinkage of concrete. In this study, the shrinkage of the granite rock in Hong Kong was measured. It has been found that the rock shrinks quite substantially upon drying and that its shrinkage is dependent on the initial moisture condition. Based on such observation, two alternative methods of treating the aggregate before use so as to reduce the shrinkage of concrete are proposed. Long-term shrinkage measurement of concrete made with untreated and treated aggregates revealed that the proposed methods of aggregate treatment, which are still rudimentary, can significantly reduce the shrinkage of concrete.

Introduction

Concrete shrinks as it dries during and after hardening. This will lead to significant shortening movement of the concrete structure and, if the shortening movement is restrained by rigid supports, cracking of the concrete structure. The shrinkage cracks so formed often cause aesthetic, water leakage and other serviceability problems. In the long run, they will also cause durability problems. One common way of alleviating shrinkage cracking is to relieve the movement restraints so as to allow unrestrained shrinkage movement by the provision of movement joints or late-cast strips (Kim and Cho, 2004; Kwan *et al.*, 2002). However, architects hate movement joints, which limit the function of the structure, and contractors hate late-cast strips, which cause delay of the construction. In this regard, perhaps one possible better solution is to reduce the shrinkage of concrete – the root cause of these problems. The possibility of reducing the shrinkage of concrete is of course yet to be investigated; most engineers regard the shrinkage of concrete as an unavoidable natural phenomenon and have never considered such a possibility.

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Although there has been extensive research on the shrinkage of concrete (Ayano and Wittmann, 2002; Barr *et al.*, 2003; Bazant *et al.*, 1987; Bissonnette *et al.*, 1999; Bloom and Bentur, 1995; Hansen and Almudaiheem, 1987), the mechanism of concrete shrinkage is still not fully understood. Nevertheless, it is now generally accepted that the major factors affecting the shrinkage of concrete include at least the aggregate properties, aggregate content, water content, cementitious materials, curing conditions, environmental conditions and member size and shape. A number of shrinkage models for prediction of concrete shrinkage have been given in British Standard BS 5400 (BSI, 1990), CEB–FIP Model Code (CEB–FIP, 1993), Eurocode 2 (BSI, 2004) and ACI code 209.2R-08 (ACI, 2008). However, they consider different factors and do not quite agree with each other. Somehow, they all have the common feature of ignoring the possible effects of the type of aggregate used, which can be quite significant (Alexander and Mindess, 2005). On the other hand, the shrinkage of Hong Kong concrete has been found to be substantially larger than that predicted by any of the existing codified shrinkage models (Highways Department, 2002, 2006; Kwan *et al.*, 2010). The authors are of the view that the relatively high water absorption and relatively low elastic modulus of the local granite aggregate (Lee *et al.*, 2000) are both contributing factors to the large shrinkage of Hong Kong concrete. Furthermore, they suspect that the aggregate may also shrink when the concrete dries and the shrinkage of the aggregate is another contributing factor to the large shrinkage of Hong Kong concrete.

There has been little research on the shrinkage of granite rock and thus whether the local granite aggregate would also shrink when the concrete dries has been a controversial issue. To resolve this, the present authors have decided to measure the shrinkage of granite rock cores obtained locally. As will be reported in the present study, the results revealed that the shrinkage of the local granite rock could amount to 380 $\mu\varepsilon$ (note; $1\ \mu\varepsilon = 1 \times 10^{-6}$) and that the shrinkage of the granite rock is dependent on the initial moisture condition. This settles the long-term controversy and explains why the shrinkage of Hong Kong concrete is so large. More importantly, the initial moisture condition of the rock aggregate, which has been ignored by most other researchers, is also a factor affecting the shrinkage of concrete.

Taking a step further, the current authors are considering the possibility of reducing the shrinkage of concrete by controlling the initial moisture condition of the rock aggregate. As the shrinkage of rock aggregate is larger when the aggregate is wet and smaller when the aggregate is dry before being added to the concrete mix, one simple way of reducing the shrinkage of concrete is to dry the aggregate before use. However, since the aggregate would become wet again after mixing with the water in the concrete mix, such simple drying is expected to have limited effectiveness. For higher effectiveness, the authors are proposing in this study to treat the aggregate before drying by immersion in polymer latex or water repellent, which fills the pores in the aggregate to block or slow down water ingress when the aggregate is added to the concrete mix.

In the present paper, the results of a testing programme that aims to measure the shrinkage of the local granite rock and the shrinkage of concrete made with untreated and treated granite aggregates are reported. It will be seen that the proposed aggregate treatment could be an emerging technology for reducing concrete shrinkage and alleviating shrinkage cracking of concrete structures.

Testing programme

The testing programme comprised two parts, termed part A and part B. Part A was to measure the shrinkage of the local granite rock under different initial moisture conditions, whereas part B was to measure the shrinkage of concrete made with granite aggregate from the same source, but with different treatment applied.

For part A, granite rock cores obtained locally from ground investigation works were tested. All the rock cores were from the same source. They have the same diameter of 60 mm and were cut into 250 mm length specimens for the shrinkage tests. The rock core specimens were divided into four groups, each comprising three specimens. The four groups were termed RC1, RC2, RC3 and RC4, and the three specimens in each group were termed (a), (b) and (c).

The rock cores in RC1 were untreated and simply stored in the laboratory at a temperature of 22–27°C and a relative humidity of 60–75% for 1 month so that their initial moisture condition may be described as 'as supplied'. For the rock cores in RC2, water immersion was applied by immersing them in a water bath at a temperature of 27°C for 7 days. For the rock cores in RC3, vacuum saturation was applied by immersing them in water inside a vacuum chamber at a pressure lower than 0·1 of the atmospheric pressure and a temperature of 27°C for 1 day. Finally, for the rock cores in RC4, drying was applied by putting them into a condition chamber set at a temperature of 50°C and a relative humidity of 50% for 7 days.

After the above treatment, all the rock cores were immersed in water for 6 h at 27°C to simulate the wetting and water absorption of the rock aggregate while the concrete is still fresh. Having been immersed in water for 6 h, the rock cores were then put into a condition chamber maintained at a temperature of 27 ± 2°C and a relative humidity of $50 \pm 2\%$ for shrinkage tests.

For part B, concrete mixes made with the local granite aggregate were cast for shrinkage testing. All the aggregates, including the fine aggregate, 10 mm aggregate and 20 mm aggregate, were from the same source. They were divided into six groups, each treated differently before use. The six groups were termed A1, A2, A3, A4, B1 and B2. The aggregates in A1, A2, A3 and A4 were treated in exactly the same ways as the rock cores in RC1, RC2, RC3 and RC4, respectively, whereas the aggregates in B1 and B2 were treated by the proposed treatment methods.

Table 1 summarises the treatment applied to the six groups of aggregate. For the aggregates in B1, they were first immersed in a 20% solution of Ronafix™ (a polymer latex) for 6 h, rinsed by clean water for 15 min and then dried in a condition chamber at a temperature of 50°C and a relative humidity of 50% for 7 days. For the aggregates in B2, they were first immersed in a 0·6% solution of Darapel™ (a water repellent) for 6 h, rinsed by clean water for 15 min and then dried in a

Table 1. Treatment applied to aggregate

Aggregate designation	Treatment applied
A1	As supplied
A2	Water immersion
A3	Vacuum saturation
A4	Drying at 50°C
B1	Immersion in polymer latex for 6 h before drying
B2	Immersion in water repellent for 6 h before drying

condition chamber at a temperature of 50°C and a relative humidity of 50% for 7 days. (The product information for Ronafix and Darapel may be obtained from the websites www.ronacrete.com and www.graceconstruction.com, respectively.) To study the effects of such treatments on the water absorption of the aggregates, the water absorption values of the aggregates in A1, B1 and B2, that is the aggregates before and after treatment, were measured in accordance with the method given in BS 812: Part 2: 1995 (BSI, 1995).

Six concrete mixes, all of grade 40, were cast from the aggregates. They have the same mix proportions, as presented in Table 2, but were each made with aggregates that had been treated differently. The concrete mixes were termed CON1, CON2, CON3, CON4, CON5 and CON6, and were made with aggregates from A1, A2, A3, A4, B1 and B2, respectively. From each concrete mix, three cubes, termed (1), (2) and (3), were cast for compressive strength tests and four prisms, termed (i), (ii), (iii) and (iv), were cast for shrinkage tests. The cubes were of size 150 × 150 × 150 mm and the prisms were of size 75 × 75 × 250 mm. Steel moulds were used for casting of these specimens. Immediately after casting, the trowelled surfaces of the specimens were covered with plastic sheets so that all surfaces of the specimens were protected from drying. The specimens were demoulded 24 h after casting. Then, the cubic specimens were cured in a lime-saturated water tank at a temperature of 27 ± 2°C until the age of 28 days and the prismatic specimens were cured by covering with wet hessian at room temperature (within 22–27°C) until the age of 7 days.

After the curing period, each prismatic specimen was coated at the two end surfaces and the top and bottom surfaces by an impermeable polymer-latex-impregnated cement mortar so that only the two side surfaces would be subjected to drying. With only the two side surfaces subjected to drying, the effective thickness of the prismatic specimen is the same as the breadth, that is 75 mm. Having been coated, the prismatic specimens were put into a condition chamber maintained at a temperature of 27 ± 2°C and a relative humidity of 50 ± 2% for shrinkage tests.

The shrinkage strains of the rock cores and the concrete prisms were measured using the apparatus stipulated in BS 812: Part 120: 1989 (BSI, 1989). During the first month, the shrinkage strains were measured every day and thereafter, as the shrinkage slowed down, the shrinkage strains were measured at successively reduced frequency up to at least 600 days of drying.

Altogether, 12 rock cores and 24 concrete prisms have been tested for their shrinkage, 18 concrete cubes have been tested for their compressive strength and 18 aggregate samples have been tested for their water absorption. Overall, the testing programme lasted over 3 years.

Shrinkage of rock

The shrinkage–time curves of the rock cores in the groups RC1 and RC2, and the rock cores in the groups RC3 and RC4, are presented in Figures 1 and 2, respectively. For each group of rock cores, the shrinkage–time curves of all three rock cores having the same treatment applied and the same initial moisture condition are plotted in these figures. In all cases, the shrinkage–time curves of the rock cores in the same group are fairly close to each other, with differences in the measured shrinkage strain generally less than 50 με. Hence, it may be said that the measured results are reasonably consistent. For easier interpretation, the shrinkage strains of the three rock cores in each group are averaged to yield the average shrinkage–time curves of the four groups of rock cores in Figure 3.

From the shrinkage–time curves plotted, it can be seen that, in general, the shrinkage increased with time initially at a rapid rate and then at a gradually decreasing rate until after several months the shrinkage increased only marginally with time. Basically, after a year or so, the shrinkage became quite steady. From

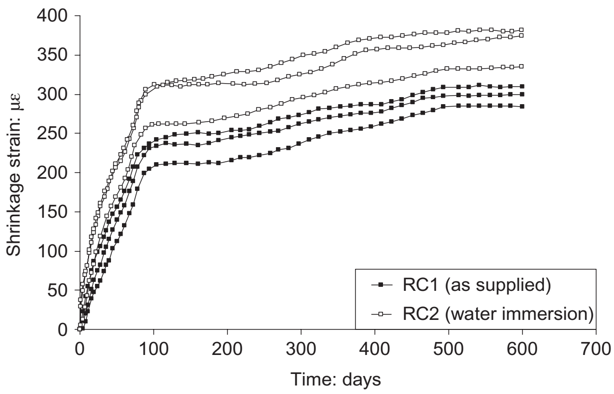

Figure 1. Shrinkage of rock cores RC1 and RC2

Table 2. Concrete mix proportions

Grade: MPa	Paste volume: %	Water content: kg/m³	Cement content: kg/m³	Fine aggregate: kg/m³	10 mm aggregate: kg/m³	20 mm aggregate: kg/m³
40	30	179	374	764	352	703

Notes: 1. The target mean strength and slump were 53 MPa and 150 mm, respectively. 2. The water/cement ratio was 0·48. 3. The fines/total aggregate ratio was 0·42. 4. A solid powder superplasticiser was added during concrete mixing until the slump of the concrete mix reached 150 mm.

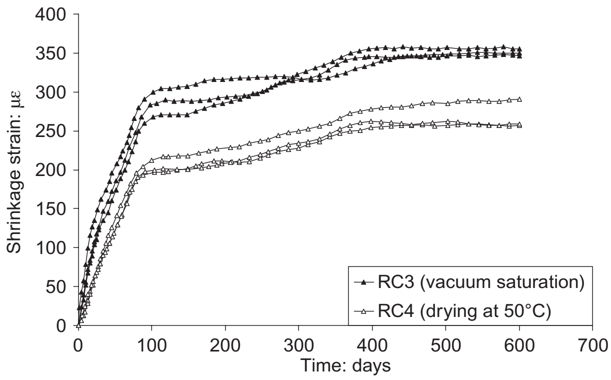

Figure 2. Shrinkage of rock cores RC3 and RC4

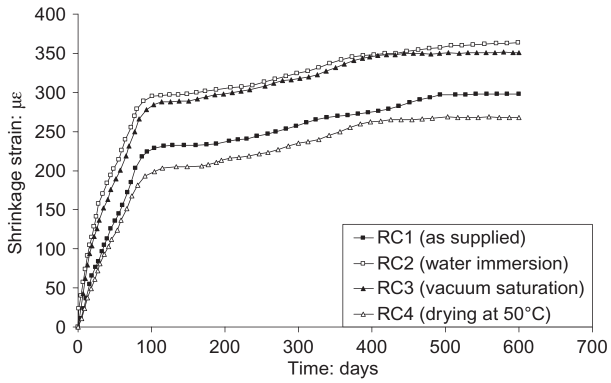

Figure 3. Average shrinkage strains of rock cores RC1 to RC4

each shrinkage–time curve, the ultimate shrinkage is determined as the shrinkage strain at the end of the shrinkage test (after at least 600 days of drying shrinkage) and the shrinkage half-time is determined as the time taken for the shrinkage to reach half of the ultimate shrinkage. The ultimate shrinkage and shrinkage half-time of the rock cores tested are presented in Tables 3 and 4, respectively.

The above results show that for the rock cores tested, the ultimate shrinkage ranges from 257 to 381 με, and the shrinkage half-time ranges from 37 to 64 days. These values of ultimate shrinkage are very substantial. Bearing in mind that the ultimate shrinkage of concrete is normally within the range 400–1000 με, such measured shrinkage of the local granite rock amounts to at least one-third of the shrinkage of the concrete. The traditional belief that granite rock would not shrink is wrong. The plain fact is that not all granite rocks are non-shrinking. Particularly, for the case in Hong Kong, it is the shrinkage of the local granite rock that causes the large shrinkage of the concrete produced (Kwan *et al.*, 2010).

On the other hand, the shrinkage half-time should be interpreted with respect to the size of the rock cores tested. The rock cores have a diameter of 60 mm and thus an effective thickness of 30 mm (the effective thickness is equal to two times the volume/exposed area ratio). In theory, the shrinkage half-time should increase with the effective thickness. Using the formula given in Eurocode 2, the shrinkage half-time for an effective thickness of 75 mm, which will be used for later comparison between rock and concrete, may be evaluated as four times the shrinkage half-time for an effective thickness of 30 mm. Hence, if the effective thickness is corrected to 75 mm, the shrinkage half-time of the rock cores would range from 148 to 256 days.

It is also evident from Tables 3 and 4 that the initial moisture condition has significant effects on the ultimate shrinkage and shrinkage half-time. For the rock cores in RC1, which were untreated and simply stored in the laboratory before the wetting and drying for the shrinkage test, the average ultimate shrinkage strain

Table 3. Ultimate shrinkage of rock cores under different initial moisture conditions

Rock core designation	Initial moisture condition	Ultimate shrinkage strain: με			
		Specimen (a)	Specimen (b)	Specimen (c)	Average
RC1	As supplied	310	284	299	298
RC2	Water immersion	331	381	373	362
RC3	Vacuum saturation	350	347	355	351
RC4	Drying at 50°C	257	289	259	268

Table 4. Shrinkage half-time of rock cores under different initial moisture conditions

Rock core designation	Initial moisture condition	Shrinkage half-time: days			
		Specimen (a)	Specimen (b)	Specimen (c)	Average
RC1	As supplied	46	64	38	49
RC2	Water immersion	47	42	40	43
RC3	Vacuum saturation	37	47	47	44
RC4	Drying at 50°C	53	54	53	53

was 298 με and the average shrinkage half-time was 49 days. For the rock cores in RC2 and RC3, which were saturated with water before the shrinkage test, the average ultimate shrinkage strains were 362 and 351 με, respectively, and the average shrinkage half-times were 43 and 44 days, respectively. Finally, for the rock cores in RC4, which were dried at 50°C before the wetting and drying for the shrinkage test, the average ultimate shrinkage strain was 268 με and the average shrinkage half-time was 53 days. Hence, quite obviously, the initially wet rock cores have larger ultimate shrinkage and shorter shrinkage half-time, whereas the initially dry rock cores have smaller ultimate shrinkage and longer shrinkage half-time. Comparing the ultimate shrinkage strains of the different rock cores, it may be worked out that the initial moisture condition could affect the ultimate shrinkage of the rock by up to 25%.

Shrinkage of concrete

The water absorptions of the granite aggregate before and after treatment by immersion in polymer latex or water repellent have been measured and the results are presented in Table 5. It can be seen that without any treatment, the fine aggregate, 10 mm aggregate and 20 mm aggregate (i.e. those in A1) have water absorptions of 1·54, 0·95 and 0·76%, respectively. After treatment by immersion in polymer latex for 6 h and then drying at 50°C, the fine aggregate, 10 mm aggregate and 20 mm aggregate (i.e. those in B1) have water absorptions of 1·09, 0·77 and 0·59%, respectively. Similarly, after treatment by immersion in water repellent for 6 h and then drying at 50°C, the fine aggregate, 10 mm aggregate and 20 mm aggregate (i.e. those in B2) have water absorptions of 1·06, 0·77 and 0·67%, respectively. Hence, by immersing the aggregate in polymer latex or water repellent for 6 h, the water absorption of the aggregate can be significantly reduced. This indicates that the polymer latex and water repellent are effective in filling the pores in the aggregate to block or slow down the ingress of water when the aggregate is wetted.

The 28-day cube compressive strengths of the six concrete mixes have been measured and the results are presented in Table 6. All the concrete mixes have achieved a mean cube compressive strength of at least 51·4 MPa. Hence, the various treatments applied to the aggregate have little effect on the concrete strength. Although the treatments applied to the aggregates in B1 and B2 appear to have a certain effect on the concrete strength, there should be no difficulty in making up such slight reduction in concrete strength by lowering the water/cement ratio of the concrete mix.

The shrinkage–time curves of the concrete prisms cast from the concrete mixes CON1, CON2, CON3, CON4, CON5 and CON6 are presented in Figures 4, 5, 6, 7, 8 and 9, respectively. For each concrete mix, the shrinkage–time curves of all the four prisms cast are plotted in these figures. In all cases, the shrinkage–time curves of the prisms cast from the same concrete mix are fairly close to each other, with differences in the measured shrinkage strain generally less than 100 με. Hence, it may be said that the measured results

Table 5. Water absorption of aggregate

Aggregate designation	Water absorption: %		
	Fine aggregate	10 mm aggregate	20 mm aggregate
A1	1·54	0·95	0·76
B1	1·09	0·77	0·59
B2	1·06	0·77	0·67

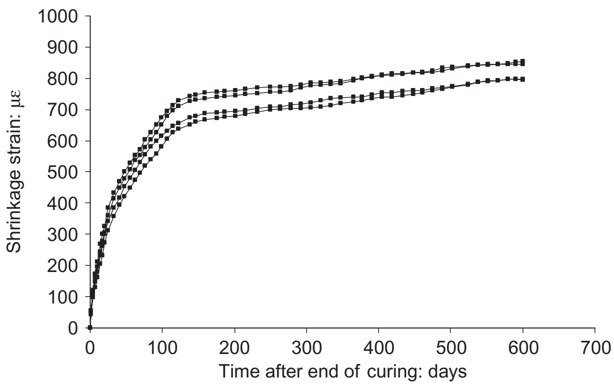

Figure 4. Shrinkage of concrete mix CON1 (A1 aggregate used)

Table 6. Cube compressive strength of concrete mixes

Concrete mix designation	Aggregate used	28-day cube compressive strength: MPa			
		Specimen (1)	Specimen (2)	Specimen (3)*	Average
CON1	A1	56·4	57·7	57·0	57·0
CON2	A2	52·5	53·9	52·0	52·8
CON3	A3	57·6	57·9	57·3	57·6
CON4	A4	52·7	53·9	51·3	52·6
CON5	B1	50·6	52·2	–	51·4
CON6	B2	52·0	52·3	52·7	52·3

*Specimen (3) of CON5 was damaged during handling.

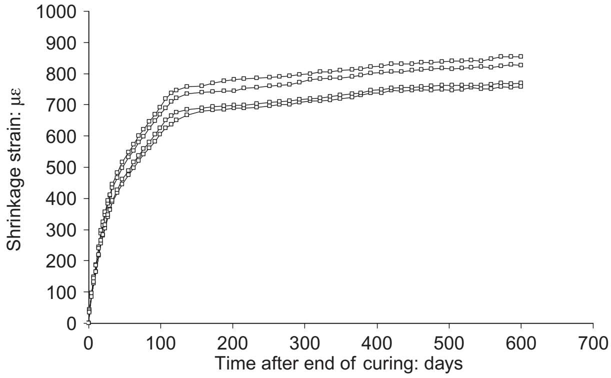

Figure 5. Shrinkage of concrete mix CON2 (A2 aggregate used)

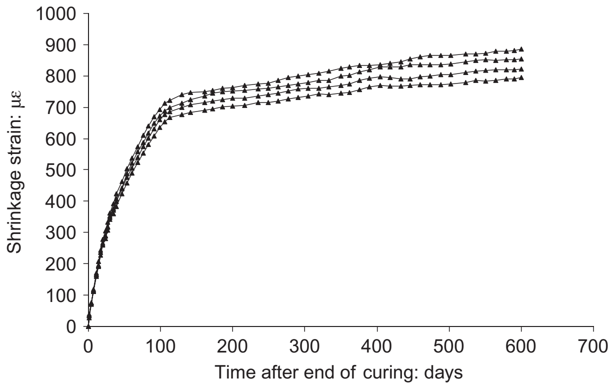

Figure 6. Shrinkage of concrete mix CON3 (A3 aggregate used)

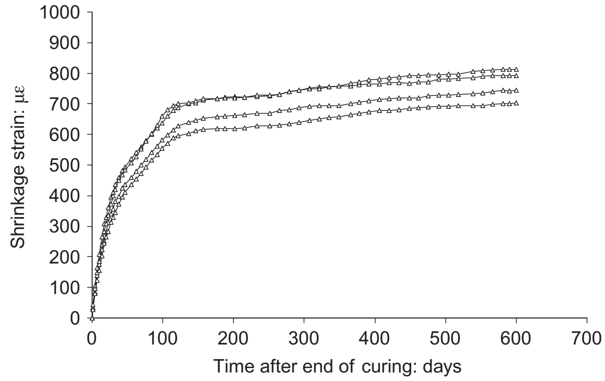

Figure 7. Shrinkage of concrete mix CON4 (A4 aggregate used)

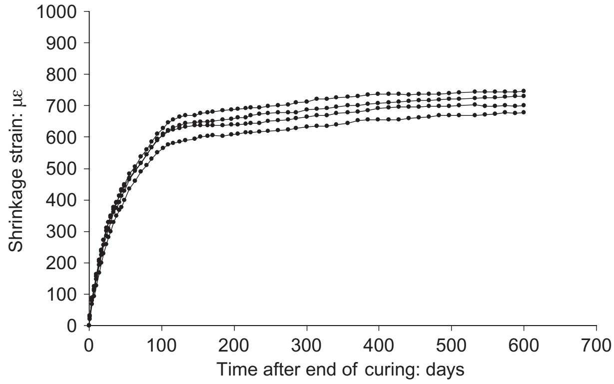

Figure 8. Shrinkage of concrete mix CON5 (B1 aggregate used)

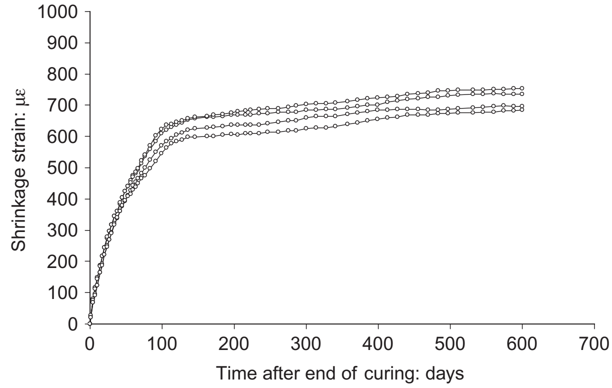

Figure 9. Shrinkage of concrete mix CON6 (B2 aggregate used)

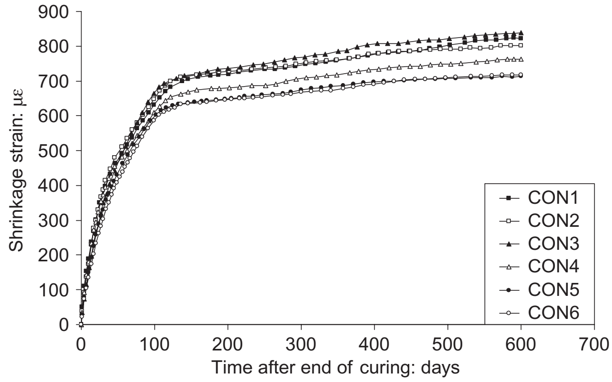

Figure 10. Average shrinkage strains of concrete mixes CON1 to CON6

are reasonably consistent. For easier interpretation, the shrinkage strains of the four prisms cast from each concrete mix are averaged to yield the average shrinkage–time curves of the six concrete mixes in Figure 10.

Like that of the rock cores, the shrinkage of the concrete prisms also increased with time initially at a rapid rate and then at a gradually decreasing rate. From each shrinkage–time curve, the ultimate shrinkage (the shrinkage strain after at least 600 days of drying) and the shrinkage half-time (the time taken for half of the ultimate shrinkage to take place) are determined, as presented in Tables 7 and 8.

The above results show that for the concrete mixes made with the aggregates from A1, A2, A3 or A4 (aggregates which had not been treated by the proposed methods of immersion in polymer latex or water repellent), the ultimate shrinkage ranges from 701 to 885 με while the shrinkage half-time ranges from 27 to 42 days. These results are similar to the previous results obtained by the authors in an earlier study on the shrinkage of Hong Kong granite aggregate concrete

Table 7. Ultimate shrinkage of concrete mixes

Concrete mix designation	Aggregate used	Ultimate shrinkage strain: με				
		Specimen (i)	Specimen (ii)	Specimen (iii)	Specimen (iv)	Average
CON1	A1	851	846	798	794	822
CON2	A2	779	827	853	788	812
CON3	A3	855	885	794	822	839
CON4	A4	742	795	815	703	764
CON5	B1	744	731	701	671	712
CON6	B2	735	753	697	684	717

Table 8. Shrinkage half-time of concrete mixes

Concrete mix designation	Aggregate used	Shrinkage half-time: days				
		Specimen (i)	Specimen (ii)	Specimen (iii)	Specimen (iv)	Average
CON1	A1	36	31	41	36	36
CON2	A2	33	32	32	33	33
CON3	A3	42	42	41	41	42
CON4	A4	32	27	32	32	31
CON5	B1	33	35	31	37	34
CON6	B2	39	40	40	40	40

(Kwan *et al.*, 2010). It should be noted that the shrinkage of these concrete mixes made with the local granite aggregate is on average quite large. Furthermore, the shrinkage of the concrete is to some extent dependent on the initial moisture condition of the aggregate. For instance, the concrete mixes CON1, CON2 and CON3 made with as supplied or saturated aggregates have average ultimate shrinkage strains of about 824 με, while the concrete mix CON4 made with pre-dried aggregate has an average ultimate shrinkage strain of 764 με, which is about 60 με or 7% smaller.

The above results also show that for the concrete mixes made with the aggregates from B1 or B2 (aggregates which had been treated by the proposed methods of immersion in polymer latex or water repellent), the ultimate shrinkage ranges from 671 to 753 με while the shrinkage half-time ranges from 31 to 40 days. Specifically, the concrete mix CON5 made with the aggregates from B1 has an average ultimate shrinkage strain of 712 με while the concrete mix CON6 made with the aggregates from B2 has an average ultimate shrinkage strain of 717 με. Compared to that of CON1 made with as supplied aggregate, the average ultimate shrinkage strain of CON5 is 110 με smaller, while the average ultimate shrinkage strain of CON6 is 105 με smaller. Hence, the proposed aggregate treatments of immersion in polymer latex or water repellent and then drying can reduce the concrete shrinkage by about 13%.

On the other hand, the shrinkage half-time results indicate that both the initial moisture condition of the aggregate and the treatment applied to the aggregate have no obvious effects on the shrinkage half-time of the concrete produced. For comparison, it is noteworthy that after correcting to an effective thickness of 75 mm, the shrinkage half-time of the concrete prisms tested ranges from 27 to 42 days while the shrinkage half-time of the rock cores tested ranges from 148 to 256 days. So, generally speaking, the granite rock shrinks at a slower rate than the concrete. It may thus be inferred that the effects of the shrinkage of the granite aggregate on the shrinkage of the concrete are larger at the later age than at the early age of the concrete.

Although the 13% reduction in concrete shrinkage by the proposed aggregate treatments of immersion in polymer latex or water repellent and then drying does not appear to be very effective, it is already a good start because the proposed treatment methods are still rudimentary. There is great potential for improvement. Some suggestions are as follows.

(*a*) Extend the immersion period from 6 h to at least 24 h so that more pores inside the rock aggregate would be filled with the polymer latex or water repellent.
(*b*) Apply vacuum during immersion so that even the finest pores deep inside the rock aggregate would be filled with the polymer latex or water repellent.
(*c*) Dry the treated aggregate at higher temperature and/or for a longer period of time so that the initial moisture condition of the rock aggregate would be drier.

Further research is needed to improve the proposed aggregate treatment technology. Another possibility is to combine such aggregate treatment with the addition of a shrinkage reducing admixture (Folliard and Berke, 1997) to the concrete mix so as to reduce not only the shrinkage of the aggregate but also the shrinkage of the hardened cement paste.

Conclusions

In the first part of the testing program, the shrinkage of the granite rock in Hong Kong has been measured in the form of rock cores under different initial moisture conditions. It was found that the granite rock, which is commonly used as aggregate for making concrete, could shrink by up to 380 $\mu\varepsilon$. Hence, the granite aggregate in Hong Kong is a shrinking aggregate. This is in fact the main reason for the large shrinkage of the Hong Kong granite aggregate concrete. Clearly, the conventional wisdom that granite aggregate will not shrink is not universally applicable. It was also found that the shrinkage of the granite rock is dependent on the initial moisture condition. In general, granite rock that is initially wet has larger ultimate shrinkage and shorter shrinkage half-time, whereas granite rock that is initially dry has smaller ultimate shrinkage and longer shrinkage half-time.

In the second part of the testing programme, the shrinkage of concrete mixes cast from aggregates with different initial moisture conditions and concrete mixes made with aggregates treated by immersion in polymer latex or water repellent for 6 h and then drying at 50°C has been measured in the form of concrete prisms. The results revealed that the initial moisture condition of the aggregate has certain effects on the shrinkage of the concrete and that pre-drying of the aggregate could slightly reduce the shrinkage of the concrete by about 7%. Such pre-drying of the aggregate is not very effective because the aggregate would become wet again when mixed with the water in the concrete mix. The results also revealed that the proposed treatments by immersion in polymer latex or water repellent and then drying could reduce the water absorption of the aggregate significantly and thereby reduce the shrinkage of the concrete by about 13%. Bearing in mind that this was just a first attempt, the 13% reduction in concrete shrinkage should be regarded as promising. Although such effectiveness is not really satisfactory, there is good potential for improvement. For instance, the treatment methods may be improved by extending the immersion period, applying vacuum during immersion and drying the immersed aggregate at higher temperature for a longer time. There is also the possibility of combining the proposed aggregate treatments with the addition of a shrinkage-reducing admixture to the concrete mix. Further studies along these lines are recommended.

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Discussion contributions on this paper should reach the editor by 1 December 2010