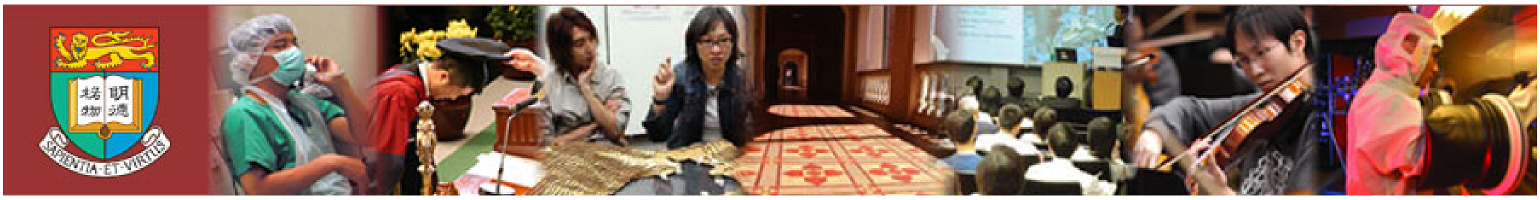

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Adding steel fibres to improve shock vibration resistance of concrete

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A newly developed shock vibration test method was employed to study the effects of shock vibration on steel-fibre-reinforced concrete so as to explore the possibility of improving the shock vibration resistance of concrete. In total, 21 batches of concrete with steel fibre contents ranging from 0 to 4% were cast and subjected to the shock vibration test at ages of 12 h, 1 day and 7 days. The results revealed that the effectiveness of adding steel fibres to alleviate the short-term damage caused by shock vibration (in terms of immediate reduction in ultrasonic pulse velocity) was quite low, especially for shock vibration applied at an early age. However, the effectiveness of adding steel fibres to mitigate the long-term damage caused by shock vibration (in terms of reduction in 28-day direct tensile strength) turned out to be much higher for shock vibration applied at age within 1 day than at later age. One probable reason is that, even after vibration damage had been caused, the continuing development of the steel–concrete bond while the concrete was still young could restore part of the reduced tensile strength. Finally, a new set of shock vibration control limits for steel fibre reinforced concrete was established.

Introduction

Concrete, especially curing concrete, is vulnerable to shock vibration damage when ground-shaking construction activities, such as rock blasting and pile driving, are carried out in close proximity.[1] It is therefore necessary to control the shock vibration generated in order to protect the nearby concrete structures from being damaged. However, there has been little research in this area and as a result the shock vibration control limits are usually set very conservatively just based on previous experience that they are safe to adopt.[2–5] The conservatively set vibration control limits have been causing severe restrictions and consequently serious delays to rock blasting and pile driving operations near concrete structures. To resolve this problem, some engineers[6,7] have been pressing to raise the vibration control limits so as to allow faster and more economical construction.

In theory, the vibration control limits should be set based on the measured shock vibration resistance of concrete. However, despite decades of research on the effects of shock vibration on concrete,[2–7] at the end of the last century there was still no consensus on how the shock vibration resistance of concrete should be determined.[8] One reason was the lack of a generally accepted test method of applying shock vibration to the concrete and measuring the damage so caused. Another reason was that the shock vibration applied in previous studies was rarely large enough to cause damage and thus the shock vibration resistance so determined was only the largest magnitude of shock vibration applied without causing significant damage. Without accurate determination of the actual shock vibration resistance of concrete and without knowing what factor of safety has been provided, the building authorities were reluctant to raise the shock vibration control limits.

Towards the end of the last century, the first author, at the request of the local government, launched a research project[9] aiming at investigating the effects of shock vibration on green concrete (i.e. curing concrete) and measuring the shock vibration resistance of concrete at different ages. After completing this project in the year 2000, the first author's research team continued the research and so far has developed a new shock vibration test method for measuring the shock vibration resistance of concrete and established a new set of shock vibration control limits that would allow more intensive ground-shaking activities to be carried out

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near existing concrete structures.[10,11] These research studies have also led to the following conclusions.

(*a*) Shock vibration has little effect on the compressive strength. It causes mainly the formation of transverse tensile cracks (tensile cracks perpendicular to the direction of shock wave propagation), which may or may not be observable on the surface. Hence, the most appropriate method of evaluating the vibration damage is to measure the reduction in direct tensile strength of the concrete in the direction of shock wave propagation.

(*b*) Although the shock vibration resistance of concrete varies with both the age and the mechanical properties of the concrete in a fairly complicated manner, the single most important parameter that governs the shock vibration resistance turns out to be the dynamic tensile strain capacity, which remains fairly constant.

The above research focused only on plain concrete. After years of research, it may now be said that the effects of shock vibration on plain concrete are basically understood. Although there is still room for improving our understanding of the erratic nature of the shock vibration resistance of concrete, it may be many more years before sufficient experimental data can be accumulated to investigate thoroughly what factors contribute to the erratic variation of the shock vibration resistance of concrete. In the meantime, with the availability of the newly developed shock vibration test method—the most important and indispensable tool for investigation—the present authors have extended the research into the second stage aiming at exploring the possibility of improving the shock vibration resistance of concrete by adding steel fibres, as reported herein. This research topic should have a high practical value because in reality it is common to cast concrete structures, such as tunnel linings and foundations, and carry out ground-shaking construction activities in the vicinity at the same time. If the shock vibration resistance of concrete could be improved by adding steel fibres, then the construction activities could be speeded up dramatically.

The addition of steel fibres to improve the impact resistance of concrete has a long history. There are already a number of laboratory tests available for determining the dynamic properties and impact resistance of steel-fibre-reinforced concrete (SFRC) (i.e. concrete containing steel fibres). These may be broadly categorised into drop weight impact tests and projectile impact tests.[12,13] A number of experimental studies on the impact behaviour of SFRC have been carried out and all of these studies, regardless of the test method employed, demonstrated that the impact resistance of SFRC is, in general, substantially higher than that of plain concrete. For example, Song *et al.*[14] applied the drop weight impact test method to evaluate the impact resistance of concrete and found that, by adding 1·5% by volume of steel fibres to an otherwise plain concrete, the average number of blows required to produce the first crack could be increased by 418% and the average number of blows required to cause failure could be increased by 518%. On the other hand, Ong *et al.*[15] applied the projectile impact test method using a projectile with a hemispherical nose and found that the amounts of impact energy required to cause failure of concrete slabs, each containing 1% or 2% by volume of steel fibres, were respectively 100% and 136% higher than that of plain concrete.

Relatively, there has been little research on the shock vibration resistance of SFRC. The nature of shock vibration resistance is quite different from that of impact resistance. First, when there is an impact, the concrete structure would at the point of impact be subjected to concentrated bending moment or punching shear force that may be large enough to cause bending or punching shear failure. On the other hand, when there is shock vibration, a shock wave would propagate through the concrete structure producing alternate tensile and compressive stresses that may be large enough to cause transverse cracking along the path of shock wave propagation. Second, most of the impact tests were performed when the concrete was fully hardened and the steel fibre–concrete matrix bond had fully developed because the concrete structure was not expected to be impact-resistant while the concrete was still green. However, most of the shock vibration tests were performed within a few days or even a few hours after casting of the concrete because concrete is generally more vulnerable to shock vibration damage when it is still green and it is the shock vibration generated by construction activities near freshly cast concrete that causes the greatest concern. Hence, although a considerable number of studies on the impact resistance of SFRC have been carried out, separate studies on the shock vibration resistance are required.

Experimental programme

In total, seven concrete mixtures with the same target mean 28-day cube strength of 50 MPa but different steel fibre contents ranging from 0 to 4% by volume were designed for testing. They were assigned mixture numbers of A, B, C, D, E, F and G, in the order of increasing steel fibre content. For all of them, ordinary Portland cement of class 52·5N was used as the only cementitious material and the water/cement ratio adopted was 0·52. The fine aggregate (5 mm maximum size) and the coarse aggregate (20 mm maximum size) were both crushed granite rock while the fine-to-total aggregate ratio was set at 0·4. A dry powder form naphthalene-based superplasticiser was added to each concrete mixture to produce a medium workability as measured in terms of V-B time. During trial mixing, it was found that as the steel fibre content increased to beyond 1%, the workability dropped quite significantly. In order to compensate for the gradual reduction in workability arising from the increasing steel fibre content, at steel fibre content higher than 1%, both the paste volume and the superplasticiser dosage were increased to maintain a reasonable workability. Table 1 summarises the mix proportions of the concrete mixtures so formulated and the corresponding V-B time measured immediately after mixing.

The type of steel fibres used in this study was Dramix RL-45/50-BN, which conforms to ASTM A820[16] and has a nominal tensile strength of 1000 MPa. Each steel fibre has a diameter of 1·05 mm and an overall length of 50 mm, corresponding to an aspect ratio of approximately 48. Hooks are formed at the ends of the fibres to provide further mechanical anchorage on top of the shear bond so as to increase the pullout strength from the concrete matrix.[17]

From each concrete mixture, three batches of concrete were produced, each batch for measuring the shock vibration resistance of the concrete at one of the three designated ages of 12 h, 1 day and 7 days. Out of each batch of concrete, six 150 mm cubes, six $\phi 150 \times 300$ mm cylinders and thirteen $100 \times 100 \times 500$ mm prisms were cast. Steel moulds were used for all specimens. The cubes and cylinders were cast vertically while the prisms were cast horizontally. They were all compacted using an internal poker vibrator. After casting, the specimens were covered with plastic sheets and stored at 20 ± 2°C. Specimens to be tested at 12 h or 1 day were demoulded at 2 h before testing, while specimens to be tested at later ages were demoulded at 1 day after casting and then water-cured at 20 ± 2°C until the time of testing.

The tests carried out on each batch of concrete are summarised below.

(*a*) Quality control tests. To ensure that each batch of concrete cast was of consistent quality, three of the cubes and three of the cylinders were tested at the standard age of 28 days to determine the cube compressive strength and split cylinder tensile strength of the concrete. Among the 13 prisms, three of them were treated as control specimens with no shock vibration applied. These three prisms were tested at the age of 28 days to determine their direct tensile strength and equivalent cube compressive strength, which were also used to check the quality of the concrete.

(*b*) Material properties tests at the time of shock vibration test. The material properties of the concrete at the time of the shock vibration test were determined by testing three of the cubes for their cube compressive strength and three of the cylinders for their split cylinder tensile strength just before the shock vibration test. In addition, the ultrasonic pulse velocity of each prism was measured both before and after the shock vibration test.

(*c*) Shock vibration tests. Among the 13 prisms, ten of them were subjected to the shock vibration test at the designated age of 12 h, 1 day or 7 days. During the shock vibration test, each prism was subjected to one hammer blow at one end of the prism in the longitudinal direction, which produced a shock wave propagating from one end to the other end. The intensity of the shock vibration applied to each prism was varied such that some of the prisms would be damaged while others not so, as to allow the determination of the shock vibration resistance of the concrete. The remaining three prisms were treated as control specimens with no shock vibration applied. After the shock vibration tests, all the 13 prisms were continued to be cured and then tested at the age of 28 days to determine their direct tensile strength and equivalent cube compressive strength.

The shock vibration tests were conducted in accordance with the method developed by the current authors in previous studies,[10,11] as illustrated by the test set-up shown in Fig. 1. Furthermore, the direct tension test method employed to determine the direct tensile strength of the prisms was the same as that developed by the present authors in 2001.[18] Apart from these, all other tests were carried out in accordance with the relevant British Standards: BS 1881: Part 104: 1983 for the V-B test;[19] BS 1881: Part 116: 1983 for the cube compression test;[20] BS 1881: Part 117: 1983 for the split cylinder tension test;[21] BS 1881: Part 203: 1986

Table 1. Mix proportions and V-B time of the concrete mixtures produced

Mixture No.	Fibre content by volume: %	Fibre weight: kg/m^3	Cement content: kg/m^3	Water content: kg/m^3	Superplasticiser: kg/m^3	V-B time: s
A	0·0	0	356	185	0·43	2·0
B	0·5	39	356	185	0·48	3·7
C	1·0	78	356	185	0·53	4·6
D	1·5	117	372	193	0·58	4·9
E	2·0	156	384	200	0·63	5·3
F	3·0	234	412	214	0·68	7·7
G	4·0	312	442	230	0·73	11·7

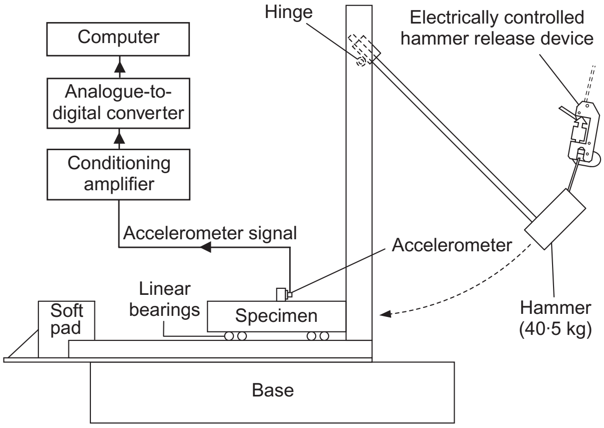

Fig. 1. Schematic diagram of test set-up for shock vibration test

for the ultrasonic pulse velocity test;[22] and BS 1881: Part 119: 1983 for the equivalent cube compression test.[23]

Experimental results

The quality control test results (i.e. the material properties of the concrete at 28-day age) are listed in Table 2. From these results, it can be seen that the mean 28-day cube strength of the seven concrete mixtures varied between 49·9 and 52·6 MPa with a range of only 5%. Hence, the seven concrete mixtures may be regarded as of the same strength grade. The coefficient of variation of the 28-day cube strength results of samples taken from the three batches of concrete made from the same concrete mixture was generally about 2 to 6%. This indicated that the batch-to-batch variation was fairly small and the three batches of concrete made from each concrete mixture were of consistent quality. On the other hand, the other results revealed that the split cylinder tensile strength, direct tensile strength and equivalent cube strength increased steadily but at different rates with the steel fibre content.

The material properties of the 21 batches of concrete at the time of performing the shock vibration test are presented in Table 3. As expected, the cube strength, split cylinder tensile strength and ultrasonic pulse velocity all increased with the concrete age. Furthermore, unlike the cube strength at 28-day age, which appeared to be independent of the steel fibre content, the cube strength at earlier ages increased significantly with the steel fibre content at a rate that was generally higher at earlier age (age $\leqslant$ 1 day) and lower at later age (age $>$ 1 day). The split cylinder tensile strength also increased significantly with the steel fibre content. However, the ultrasonic pulse velocity was basically unaffected by the steel fibre content.

During the shock vibration tests, shock vibrations of different intensities were applied to the prisms. The intensity of the shock vibration applied to each prism was measured in terms of the peak particle velocity (ppv) of the shock wave induced by the hammer blow exerted at one end of the prism. In this particular series of shock vibration tests, the maximum ppv applied to the prisms at ages of 12 h, 1 day and 7 days were 844 mm/s, 1065 mm/s and 1395 mm/s, respectively. After the shock vibration tests, the short-term effects were evaluated by observing the appearance of cracks and measuring the immediate change in ultrasonic pulse velocity, while the long-term effects were evaluated by continuing to cure the prisms until the age of 28 days and then measuring the direct tensile strength and equivalent cube strength of the prisms. For easier interpretation, the changes in ultrasonic pulse velocity, direct tensile strength and equivalent cube strength are expressed in terms of the following ratios.

(*a*) The ultrasonic pulse velocity ratio, which is defined as the ratio of the ultrasonic pulse velocity of the prism after the shock vibration test to that before the shock vibration test.
(*b*) The direct tensile strength ratio, which is defined

Table 2. Quality control test results (material properties at 28-day age)

Mixture No.	Cube compressive strength		Split cylinder tensile strength		Direct tensile strength		Equivalent cube compressive strength	
	Mean: MPa	COV: %	Mean: MPa	COV: %	Mean: MPa	COV: %	Mean: MPa	COV: %
A	50·6	2·7	3·28	9·0	2·64	5·4	49·5	4·1
B	50·6	2·1	3·49	6·8	2·87	5·6	53·2	2·1
C	51·5	2·2	3·88	4·0	2·93	6·0	57·0	2·8
D	51·5	6·3	4·59	7·2	2·99	9·2	60·7	5·1
E	50·8	4·1	4·94	6·1	3·34	4·7	62·4	3·4
F	52·6	4·1	6·11	10·3	3·56	4·5	66·6	5·1
G	49·9	2·1	6·50	6·2	3·70	3·5	63·0	4·0

COV = coefficient of variation.
Each value presented herein is based on the test results of nine specimens cast from three batches of the same concrete mixture.

Table 3. Material properties at time of performing shock vibration test

Mixture No.	Age	Cube compressive strength: MPa	Split cylinder tensile strength: MPa	Ultrasonic pulse velocity: m/s
A	12 h	3·6	0·37	2753
	1 day	11·8	1·16	3383
	7 days	36·2	2·97	4336
B	12 h	5·3	0·56	2997
	1 day	12·8	1·27	3317
	7 days	38·3	2·96	4130
C	12 h	8·4	0·98	2930
	1 day	13·7	1·50	3328
	7 days	39·7	3·24	4312
D	12 h	8·6	1·06	2935
	1 day	13·6	1·50	3203
	7 days	41·1	3·86	4309
E	12 h	9·1	1·28	3002
	1 day	19·7	2·45	3435
	7 days	42·6	4·62	4323
F	12 h	11·8	1·32	2869
	1 day	22·8	2·97	3524
	7 days	41·4	5·00	4366
G	12 h	10·0	1·44	2828
	1 day	22·0	3·10	3405
	7 days	40·4	5·15	4278

The ultrasonic pulse velocity results were those of the three prisms taken as control specimens.
Each value presented herein is the mean value of three specimens tested.

as the ratio of the 28-day direct tensile strength of the prism to the mean 28-day direct tensile strength of the prisms not subjected to any shock vibration (the control specimens).

(*c*) The equivalent cube strength ratio, which is defined as the ratio of the 28-day equivalent cube strength of the prism to the mean 28-day equivalent cube strength of the prisms not subjected to any shock vibration (the control specimens).

The effects of shock vibration are studied in terms of these ratios in the following sections.

Effects of shock vibration

Formation of cracks

Among the 210 prisms subjected to shock vibration up to intensities that should be large enough to cause significant damage, only 11 prisms had been cracked. One of the 11 cracked prisms, which was cast of plain concrete (i.e. cast of concrete mixture A) and was subjected to shock vibration at 7 days up to a ppv of 1186 mm/s, was actually broken into two pieces. The other ten cracked prisms were found to have transverse hairline cracks formed within the middle third along the length of the prisms. These cracks were all so fine that they were hardly observable even under the most favourable lighting condition. Moreover, they were all found on prisms cast of concrete with steel fibre content less than 2% (i.e. cast of concrete mixtures A, B, C or D). No visible crack was found on prisms cast of concrete with steel fibre content equal to or higher than 2% (i.e. cast of concrete mixtures E, F or G).

All the cracked prisms had direct tensile strength ratios lower than 0·8 (i.e. had their direct tensile strength reduced by more than 20% compared with the mean of the control specimens cast of the same concrete). Hence, regardless of whether or not the concrete contains steel fibres, when a crack is observed, it is almost certain that the tensile strength of the concrete has been significantly reduced. On the other hand, among the prisms whose direct tensile strength ratios were lower than 0·8, only 11 out of 42 (26%) had shown visible cracks and 31 out of 42 (74%) had not shown any visible cracks. This revealed that there might have been micro-cracks formed in the concrete that were unobservable by naked eyes. Hence, if we just rely on the observation of cracks to detect vibration damage, there will be a missing rate of 74%. Such a high missing rate is unacceptable and therefore observation of cracks is not a reliable method of detecting vibration damage.

The above missing rate is higher than that for plain concrete derived from previous studies.[10,11] This may be attributed to the high effectiveness of the steel fibres in controlling cracking, which rendered the cracks formed due to shock vibration to be hardly observable or even unobservable. Hence, the high missing rate is not a bad thing; the present results simply demonstrate that at a steel fibre content of 2% or higher, the steel fibres added are quite effective in controlling the cracking of concrete afflicted by shock vibration damage.

Ultrasonic pulse velocity

The effects of the shock vibration applied on the ultrasonic pulse velocity of the concrete are studied by plotting the ultrasonic pulse velocity ratio against the ppv of the shock vibration, as shown in Fig. 2. As the effects of shock vibration on ultrasonic pulse velocity are highly dependent on the concrete age, the data points are plotted in three separate graphs, each for one concrete age at which the shock vibration tests were carried out. It can be seen from these graphs that although the data points are quite scattered, on the whole as revealed by the trend lines drawn alongside the data points, regardless of the concrete age and the steel fibre content, the ultrasonic pulse velocity ratio decreased significantly when the ppv increased. Since

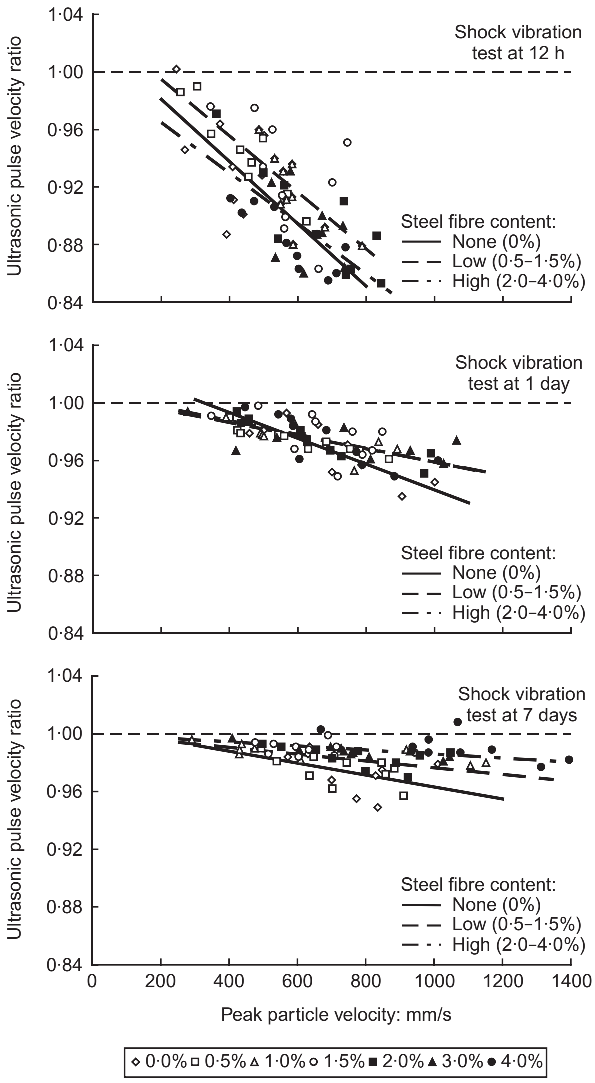

Fig. 2. Ultrasonic pulse velocity ratio plotted against peak particle velocity

the reduction in ultrasonic pulse velocity ratio is in some sense a measure of the extent of damage, this indicated that the short-term damage caused by shock vibration was generally larger at higher ppv.

Comparing the three graphs, it is noted that the reduction in ultrasonic pulse velocity due to shock vibration was substantially larger at earlier concrete age. This was expected because concrete is generally more vulnerable to shock vibration damage at earlier age. Comparing the trend lines, it is also noted that with steel fibres added, the rate of reduction in ultrasonic pulse velocity with the ppv had become slower (as depicted by the more gentle slopes of the trend lines). Hence, at the same ppv, the short-term damage caused to concrete containing steel fibres was generally less severe than that caused to plain concrete. Nevertheless, at an early age of 12 h, there was little difference between the rate of reduction in ultrasonic pulse velocity for concrete containing steel fibres and that for plain concrete (as depicted by the very close trend lines), indicating that the short-term damage caused to concrete containing steel fibres was very much the same as that caused to plain concrete. Hence, at an age of 12 h, the addition of steel fibres has rather low effectiveness in alleviating the short-term damage caused by shock vibration. However, care should be taken not to infer at this stage that the addition of steel fibres is of little use; it will be shown later that, owing to continuing development of the steel–concrete bond, the steel fibres could restore part of the reduced tensile strength owing to the short-term damage and thereby improve the shock vibration resistance at such age.

Direct tensile strength

The effects of the shock vibration applied on the 28-day direct tensile strength of the concrete are studied by plotting the direct tensile strength ratio against the ppv of the shock vibration, as shown in Fig. 3. As before, since the effects of shock vibration are dependent on the concrete age, the data points are plotted in three separate graphs, each for one concrete age at which the shock vibration tests were carried out. From the trend lines drawn alongside the data points, it can be seen that apart from some erratic variations, regardless of the concrete age and the steel fibre content, the direct tensile strength ratio decreased when the ppv increased, showing clearly that the long-term damage caused by shock vibration was generally larger at higher ppv.

The results for the shock vibration tests carried out at 12 h showed that the direct tensile strength ratio of plain concrete decreased significantly when the ppv increased (as depicted by the steep trend line) while the direct tensile strength ratio of concrete containing steel fibres remained more or less the same even when the ppv increased to fairly large values (as depicted by the almost horizontal trend lines). In fact, after subjected to shock vibration, all the prisms cast of concrete contain-

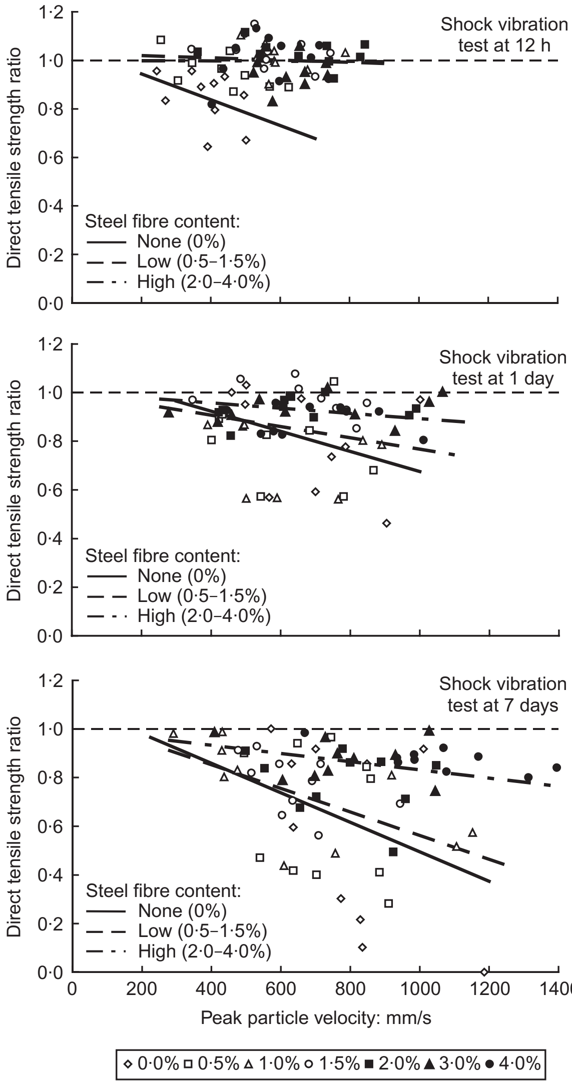

Fig. 3. Direct tensile strength ratio plotted against peak particle velocity

ing steel fibres had their direct tensile strength ratios remaining higher than 0·8 (reduction in direct tensile strength less than 20%) and some even had their direct tensile strength ratios higher than 1·0 (no reduction in direct tensile strength). Hence, although the addition of steel fibres is not really effective in alleviating the short-term damage caused by shock vibration applied at 12 h, in the longer term, provided enough steel fibres have been added and the concrete has subsequently been properly cured, the 28-day direct tensile strength of the concrete subjected to shock vibration at 12 h could be kept at not less than 0·8 times that of the same concrete not subjected to any shock vibration. Based on these 28-day direct tensile strength results, it may be concluded that the addition of steel fibres is actually quite effective in improving the shock vibration resistance of concrete at the age of 12 h.

The results for the shock vibration tests carried out at 1 day and 7 days also showed that the reduction in direct tensile strength ratio with the ppv was generally smaller for the concrete containing steel fibres than for the plain concrete. Hence, the addition of steel fibres is also effective in improving the shock vibration resistance of concrete at such ages. Relatively, since after having been subjected to shock vibration, some of the prisms cast of concrete containing steel fibres had their direct tensile strength ratios falling below 0·8, the addition of steel fibres is less effective in improving the shock vibration resistance at such later ages than at 12 h.

Equivalent cube strength

The effects of the shock vibration applied on the 28-day equivalent cube strength of the concrete are studied by plotting the equivalent cube strength ratio against the ppv of the shock vibration, as shown in Fig. 4. From the figure, it can be seen that the equivalent cube strength ratios of nearly all the prisms, regardless of the steel fibre content, the concrete age at which the shock vibration was applied and the intensity of the shock vibration applied, lie within the narrow range between 0·9 and 1·1. There are only a few data points with equivalent cube strength ratios falling outside this range. These few outliers were most probably attributable to variations in material properties and experimental errors. Hence, shock vibration up to the intensities applied in the present study has basically no effect on the compressive strength of the concrete, regardless of whether the concrete contains steel fibres or not.

Correlation between short- and long-term damages

In previous sections, it was found that the ultrasonic pulse velocity ratio and the direct tensile strength ratio are the most appropriate measures for evaluating respectively the short- and long-term damage caused by shock vibration. Since the short-term damage was the source of the long-term damage, there should be some direct correlation between the short- and long-term damage. Such correlation is studied herein by plotting the direct tensile strength ratio against the ultrasonic pulse velocity ratio, as shown in Fig. 5. As before, the

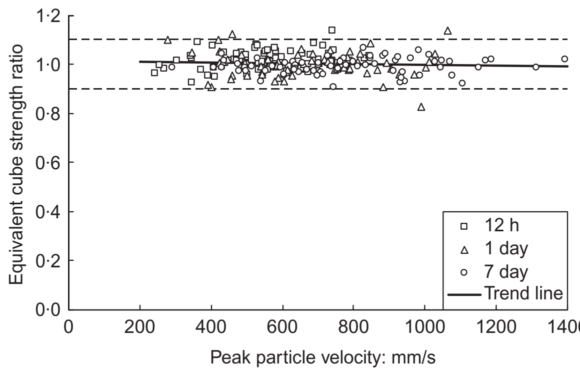

Fig. 4. Equivalent cube strength ratio plotted against peak particle velocity

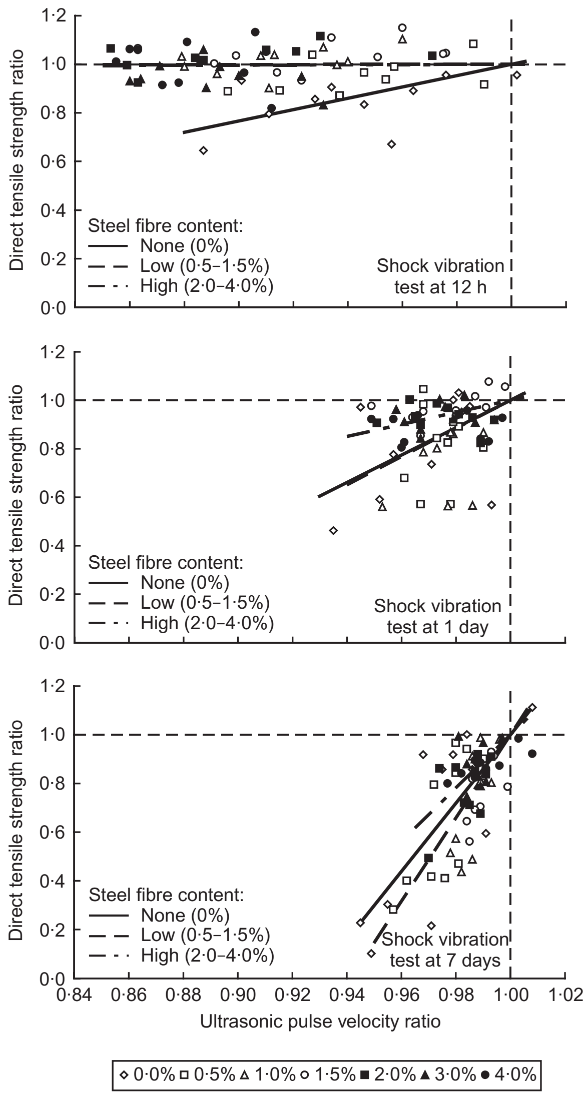

Fig. 5. Correlation between short- and long-term damage

data points are plotted in three separate graphs, each for one concrete age at which the shock vibration was applied. In each graph, trend lines are drawn alongside the data points to depict the correlation between the short- and long-term damage at different steel fibre contents.

When interpreting these graphs, it should be borne in mind that based on previous experience,[10,18] the within-test coefficient of variation of ultrasonic pulse velocity measurements repeatedly taken at the same measurement points is about 1% and the within-test coefficient of variation of direct tensile strength measurements carried out on specimens cast of the same batch of concrete is about 10%. Therefore, a reduction in the ultrasonic pulse velocity of more than 2% or a reduction in the direct tensile strength of more than 20% (i.e. reduction of more than 2 × coefficient of variation) should be regarded as a significant and detectable change.

Comparing the trend lines in the three graphs, it is evident that the correlation between the short- and long-term damage was highly dependent on both the concrete age and the steel fibre content. The results for the shock vibration tests carried out at 12 h showed that although many prisms had significant reduction in ultrasonic pulse velocity (more than 2% reduction or ultrasonic pulse velocity ratio lower than 0·98), very few of these prisms, which were all cast of plain concrete, had significant reduction in direct tensile strength (more than 20% reduction or direct tensile strength ratio lower than 0·8). In particular, the trend lines for the prisms cast of concrete containing steel fibres are almost horizontal, indicating that there was basically no correlation between the short- and long-term damage, and that albeit having incurred significant short-term damage after the shock vibration tests at 12 h, the concrete containing steel fibres was able to recover to the extent that no significant long-term damage could be detected by the 28-day tests.

On the other hand, the results for the shock vibration tests carried out at 1 day and 7 days showed that at such later ages, there was a higher correlation between the short- and long-term damage. In other words, at an age of 1 day or later, once short-term damage has been incurred after the application of shock vibration, the concrete would not fully recover and at least part of the short-term damage would remain as long-term damage. From the slopes of the different trend lines, it may also be inferred that the ability of SFRC to recover after having incurred short-term damage is higher at earlier concrete age and at a higher steel fibre content.

Effectiveness of steel fibres

Putting Figs 2, 3 and 5 together, the effectiveness of adding steel fibres to improve the shock vibration resistance of concrete may be summarised by the following. The effectiveness of adding steel fibres to alleviate the short-term damage owing to shock vibration is generally lower for shock vibration applied at earlier age and higher for shock vibration applied at later age. However, the effectiveness of adding steel fibres to improve the ability of the concrete to recover so that there would be smaller reduction in direct tensile strength at the age of 28 days is generally higher for shock vibration applied at earlier age and lower for shock vibration applied at later age. On the whole, regardless of the age of the concrete when subjected to shock vibration, a higher steel fibre content would lead to a higher effectiveness in alleviating the short-term damage and also a higher effectiveness in improving the ability of the concrete to recover.

Subject to verification by further in-depth studies, it is postulated that the gradual development of the bond between the steel fibres and the concrete matrix is the major factor governing the effectiveness of the steel fibres added to the concrete. In general, the bond of steel fibres in concrete, which comprises both physical adhesion and chemical bond, increases steadily with the concrete strength.[17] At an early age of 12 h when the concrete strength is still low, only a small portion of the bond has been developed and hence when the concrete is subjected to shock vibration, the steel fibres are not really effective in alleviating the short-term damage. However, after the shock vibration, although the bond might have been disrupted, since the cement in the concrete is still hydrating, the bond continues to develop (provided of course the concrete is properly cured) and consequently the SFRC is able to recover to the extent that there is no significant long-term damage. At later ages of 1 day or 7 days when the concrete strength is higher, a larger portion of the bond has been developed, thus rendering the steel fibres to be more effective in alleviating the short-term damage. Since at such ages, the rate of hydration of the cement has already slowed down, once the bond has been disrupted by shock vibration, the subsequent redevelopment of bond is relatively small and as a result it becomes rather difficult for the SFRC to recover.

Vibration control limits

To establish a new set of vibration control limits for SFRC, it is first necessary to determine the shock vibration resistance of the concrete at different ages and with different steel fibre contents. In previous studies,[10,11] it has been proposed to determine the shock vibration resistance of concrete as the threshold ppv that would cause more than 20% reduction in the 28-day direct tensile strength (i.e. that would lead to a direct tensile strength ratio lower than 0·8). However, since there is no way continuously to adjust the ppv of the shock vibration until the reduction in direct tensile strength is exactly 20%, such threshold ppv cannot be measured directly. Nevertheless, as proposed in the previous studies, the shock vibration resistance may be determined in terms of ppv1 and ppv2, which are defined as the lowest ppv applied that had caused more than 20% reduction in direct tensile strength and the highest ppv applied that had not caused more than 20% reduction in direct tensile strength, respectively.

The ppv1 and ppv2 values of the seven concrete mixtures at different ages so determined are presented in Table 4. As in previous studies, although in theory, the ppv causing damage should be higher than the ppv not causing damage, ppv1 is not always higher than ppv2. This is owing to the erratic nature of the shock vibration resistance of concrete, which renders the degree of damage a probabilistic rather than a deterministic function of the vibration intensity. Because of such difficulty, the shock vibration resistance (denoted hereafter by ppv3) is determined from each pair of ppv1 and ppv2 values conservatively as the minimum of ppv1 and ppv2. Where ppv1 or ppv2 has not been obtained, ppv3 is taken as the remaining available ppv value. The ppv3 values so determined are tabulated in the last column of Table 4. These ppv3 values show that there is an overall trend of increasing shock vibration resistance with both the concrete age and the steel fibre content, but partly resulting from erratic variation of shock vibration resistance and partly from experimental errors, there are a number of exceptions from this overall trend.

Table 4. Shock vibration resistances in terms of ppv1, ppv2 and ppv3

Mixture No.	Age	ppv1: mm/s	ppv2: mm/s	ppv3: mm/s
A	12 h	391	495	391
	1 day	567	1001	567
	7 days	636	1011	636
B	12 h	—	625	625
	1 day	543	753	543
	7 days	540	847	540
C	12 h	—	788	788
	1 day	501	836	501
	7 days	609	919	609
D	12 h	—	745	745
	1 day	—	848	848
	7 days	604	715	604
E	12 h	—	844	844
	1 day	—	990	990
	7 days	655	1048	655
F	12 h	—	737	737
	1 day	—	1065	1065
	7 days	605	1027	605
G	12 h	—	740	740
	1 day	—	1011	1011
	7 days	—	1395	1395

In some cases, the ppv1 value was not obtained because none of the ten prisms subjected to the shock vibration test at the same time has its direct tensile strength ratio falling below 0·8.

Before these ppv3 values can be used to establish a new set of vibration control limits, they need to be smoothened by adjusting some of the individual values downwards so that the shock vibration resistance becomes a monotonically increasing function of both the concrete age and the steel fibre content. Such adjustment is demonstrated and the resulting smoothened values, which are also lower bound values, are presented in Table 5. From the smoothened values of ppv3, it is evident that at an age of 12 h, the addition of 0·5% steel fibre can increase the shock vibration resistance by 28% while the addition of 1·5% steel fibre can increase the shock vibration resistance by 54%. At an age of 1 day, the addition of 1·5% steel fibre increases the shock vibration resistance by only 21% and any further addition of steel fibres would not be effective until the steel fibre content had reached 4%. Lastly, at an age of 7 days, the addition of 1·5% steel fibre increases the shock vibration resistance by a bare 12% and any further addition of steel fibres would

Table 5. Smoothened and lower bound values of ppv3

Fibre content: %	Original values of ppv3: mm/s			Smoothened and lower bound values of ppv3: mm/s		
	12 h	1 day	7 days	12 h	1 day	7 days
0·0	391	567	636	391	501	540
0·5	625	543	540	501	501	540
1·0	788	501	609	501	501	604
1·5	745	848	604	604	604	604
2·0	844	990	655	605	605	605
3·0	737	1065	605	605	605	605
4·0	740	1011	1395	740	1011	1395

not be effective until the steel fibre content has reached 4%. However, it should be borne in mind that the addition of steel fibres up to 4% would render the concrete mixture quite difficult to compact and very costly. In practice, steel fibres are more suitable for use at a dosage of 0·5 to 2·0% to improve the shock vibration resistance of curing concrete up to the age of 1 day.

Finally, dividing the smoothened values of ppv3 by a suitable factor of safety, which may be taken as 5·0 for important structures or 3·0 for ordinary structures, a new set of vibration control limits can be established, as tabulated in Table 6. This new set of vibration control limits would, for curing concrete containing steel fibres, allow a higher vibration control limit to be adopted and more intensive ground-shaking activities to be carried out in close proximity.

Conclusions

Based on the shock vibration test method developed by the current authors in previous studies, a comprehensive experimental programme has been launched to explore the possibility of adding steel fibres to improve the shock vibration resistance of concrete. In the programme, 21 batches of concrete were produced from seven concrete mixtures with steel fibre contents ranging from 0 to 4% for testing. In total, 525 specimens have been cast and tested to study the short- and long-term effects of shock vibration applied at concrete ages of 12 h, 1 day and 7 days.

After applying shock vibration, the short-term effects were evaluated by observing the appearance of cracks and measuring the immediate change in ultrasonic pulse velocity, while the long-term effects were evaluated by continuing to cure the specimens and measuring their 28-day direct tensile strength and equivalent cube strength. It was found that the observation of cracks is not a reliable method of detecting damage in SFRC because the high effectiveness of the steel fibres in controlling cracking would render the cracks hardly observable or even unobservable. Relatively, the change in ultrasonic pulse velocity is a much better measure of the short-term damage caused by shock vibration. On the other hand, since the compressive strength is basically unaffected, the change in 28-day direct tensile strength should be the most appropriate measure of the long-term damage.

Regarding the usefulness of steel fibres, the test results revealed that for shock vibration applied at an early age of 12 h, the addition of steel fibres has rather low effectiveness in alleviating the short-term damage but due probably to the continuing development of the steel–concrete bond while the concrete is still young, the addition of steel fibres is so effective in improving

Table 6. Recommended vibration control limits

Fibre content: %	Vibration control limits in terms of ppv: mm/s					
	Factor of safety = 5·0			Factor of safety = 3·0		
	12 h	1 day	7 days	12 h	1 day	7 days
0·0	75	100	105	130	165	180
0·5	100	100	105	165	165	180
1·0	100	100	120	165	165	200
1·5	120	120	120	200	200	200
2·0	120	120	120	200	200	200
3·0	120	120	120	200	200	200
4·0	145	200	275	245	335	465

the ability of the concrete to recover that any concrete containing not less than 0·5% steel fibres should be able to recover fully, leading eventually to no detectable long-term damage. However, for shock vibration applied at later ages of 1 day or 7 days, although the effectiveness of adding steel fibres to alleviate the short-term damage is slightly higher, the effectiveness in improving the ability of the concrete to recover is substantially lower. Overall, the addition of steel fibres is more effective in improving the shock vibration resistance of concrete at age within 1 day than at a later age.

Based on the test results, the shock vibration resistance (the threshold peak particle velocity causing 20% reduction in 28-day direct tensile strength) of SFRC at different ages and with different steel fibre contents has been determined. Adjusting the individual values of shock vibration resistance slightly downwards so that the shock vibration resistance becomes a monotonically increasing function of both the concrete age and the steel fibre content, and dividing the shock vibration resistance values by a suitable factor of safety, a new set of shock vibration control limits has been established. This new set of vibration control limits would for freshly cast SFRC allow much more intensive ground-shaking construction activities to be carried out in close proximity.

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