- Technical Paper -

ROLE OF COARSE AGGREATE IN HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITE

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ABSTRACT

An endeavor to improve crack-shear interface of HPFRCC was made by adding coarse aggregate to a given HPFRCC mixture. To reveal its effectiveness, four-point bending tests were performed on initially sound and pre-cracked plates all made of original and modified mixtures with coarse aggregate. It was found that a proper amount of aggregate could work robustly in conjunction with pre-cracking only. Significant differences were observed in terms of load-displacement relationship and crack pattern.

Keywords: HPFRCC, coarse aggregate, shear performance, crack pattern

1. INTRODUCTION

High Performance Fiber Reinforced Cementitious Composite (HPFRCC) is a cement-based material in which its high-performance is achieved through extensive collaboration between fibers and surrounding cement-based matrix. One notable characteristic of HPFRCC is seen as ductile with strain hardening behavior up to several percent in tension [1]. The majority of HPFRCC utilizes short discontinuous fibers (e.g.: PVA, PE, steel) and fine-graded materials (e.g.: silica sand, fly ash), which are combined together with cement to form a compound matrix.

One of the reasons why fine-graded material is used as cement replacement is perhaps related to the homogeneity of HPFRCC matrix. For a given fiber volume and aspect ratio, the matrix can be designed in such a way (e.g.: micromechanics design [2]) to achieve a certain matrix toughness and strength. By virtue of this design concept, it is then possible to ensure an adequate margin at any potential cracks, thereby allowing multiple cracking.

Considerable attention was therefore given to improve tensile property of cement-based material from brittle to desirable ductile behavior. As multiple cracking is one of the viable solutions, the more crack numbers means the more ductile the material is. Denser crack spacing is therefore preferred while tensile ductility in one direction is the greatest concern.

Nevertheless, cracking built up in elements of existing structures is often in multi-directions rather than simply oriented in one direction. This condition made crack interface regularly subjected to complex stress conditions, involving the actions of tensile and shear stresses normal and tangential to crack surfaces.

Recently, the authors pointed out the importance of considering shear transfer across cracked HPFRCC interface [3]. The key point of the test was by applying two different principal stress directions; one during the pre-cracking stage, and the other one during the main testing stage. It was then possible to initiate shear stress at the interface of the pre-induced, multiple cracks. The test showed that when shear stress at crack interface existed, flexural capacity decreased 30% at worst. This strengthened the raised issue that shear at crack interface is also an important factor that should not be overlooked. As far as shear is concerned, lack of coarse aggregate might be one of the reasons.

The inclusion of coarse aggregate into HPFRCC mixture was previously investigated by Wang and Li [4]. The objective was to increase the number of large flaws artificially as an alternative way to bring the cracking stress of any potential cracks lower than the bridging stress of the existing cracks. In this context, the preferred aggregate type was either low-strength aggregate (e.g.: expanded shale) or any aggregate with low bond to the matrix (e.g.: plastic beads).

The inclusion of coarse aggregate in this study is expected to increase crack-shear interface performance of HPFRCC. In contrast to the previous attempt, the aggregate here should be strong as compared to the matrix strength. At the same time, the aggregate may however decrease the ability of crack in transferring tensile stress. The trade-off between the two should be explored so as to result in an optimal solution.

The purpose of this paper is first to come up with a possible HPFRCC proportioning with coarse aggregate. The primary objective is to reveal the role of coarse aggregate by comparing the results of 23 HPFRCC plates made with and without aggregate. Particular emphasis is given to load-displacement relationships and crack pattern. Considering its practical applicability, the current investigation is limited to one HPFRCC type called PVA-ECC [5].

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2. EXPERIMENTAL PROGRAMS

2.1 General Overview

The experimental program herein involved the testing of 15 small-size plates made of modified HPFRCC mixture with coarse aggregate, hereafter designated as Group 1 and Group 2. The result was then compared with those made of original mixture, which had been tested earlier [3], hereafter designated as Group 0.

Summary of the test program is given in Table 1. Two types of plates were made: five control plates and ten main plates. The control plates were 250×400 mm in plan dimension and 20-mm thick, while the main plates were in the same thickness and 420×550 mm in plan dimension (see Fig. 1). The primary test parameters were the amounts of coarse aggregate (Group 0, 1, and 2), which will be explained later, and pre-crack orientation (none, 0, 20, 45, 70, and 90 deg).

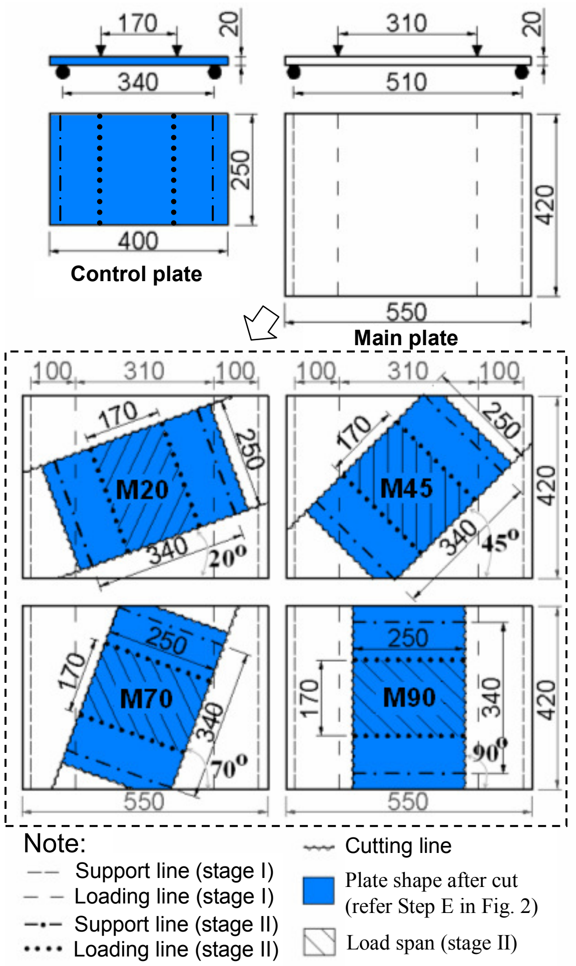

Fig.1 Typical dimension and layout of test plates

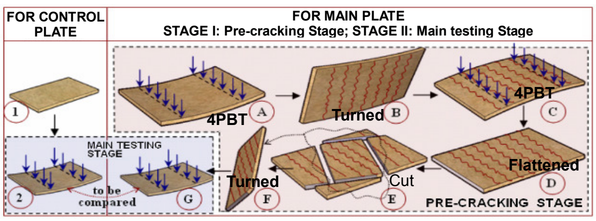

Fig.2 Testing procedure [3]

Table 1 Overview of Test Specimens

ID	Dimension W mm	Dimension L mm	Dimension H mm	Initial Damage Orientation* (degree)	Initial Damage Level % ε_{Pmax}	Specimen Type
0-C1,2 0-CR 1-C1,2 2-C1,2	250	400	20	-None-	-None-	Control
1-M0 2-M0	420	550	20	0	40	Main
0-M20 1-M20 2-M20	420	550	20	20	40	Main
0-M45 1-M45 2-M45	420	550	20	45	40	Main
0-M70 1-M70 2-M70	420	550	20	70	40	Main
1-M90 2-M90	420	550	20	90	40	Main

* Measured from the plane parallel to the width of the plate after cut
0-, 1-, and 2- implies Group 0, Group 1, and Group 2 plates respectively

The testing procedure adopted here is illustrated in Fig. 2 (for details see Ref. 3). Basically, the control plates were simply subjected to four-point bending tests (see Steps 1 and 2 in Fig. 2), whereas the main plates were pre-cracked and cut (see Step A to F in Fig. 2), and further loaded in bending until failure (see Step G in Fig. 2).

2.2 Material Selection

(1) HPFRCC

The HPFRCC used was a premix type known as PVA-ECC [5]. It is reinforced with 2% volume of 12-mm length and 0.04-mm diameter of PolyVinyl Alcohol (PVA) fibers. The mix proportion of the material is shown in Table 2.

Table 2 Mix Proportion of PVA-ECC [5]

W/(C+FA) (%)	Water (kg/m^3)	S/(C+FA) (%)	PVA Fibers (%), in vol.
42.2	350	70	2.0

Note: W: Water, C: Cement, FA: Fly Ash, S: Sand

(2) Coarse Aggregate

A locally available, crushed type, aggregate was used. The gradation is relatively uniform as shown in Table 3. Considering the thickness of the test plates, the aggregate size larger than 9.5 mm was omitted. Prior to casting, the aggregate were properly cleaned and kept in a saturated surface dry (SSD) condition.

Table 3 Original Sieve Analysis

Sieve size (mm)	Cumulative Passing (%)
19	100
13.2	95
4.75	5.7

The amount of aggregate included in Group 1 and Group 2 was about 30% and 15% of γ_{max}, respectively, where γ_{max} is the maximum packing density of aggregate for a given volume and was found to be 63%. These two aggregate amounts were judged based on the following two criteria: potential distribution of the aggregate in a certain volume and the workability after mixed with HPFRCC paste. The aggregate distribution is deemed important to ensure the presence of aggregate at any potential crack interfaces, whilst the workability is related to the ease of production. The Group 1 represented fairly large amount of aggregate addition with significant workability drop, while the Group 2 yielded a moderate aggregate addition, with minor impact on workability. Although impractical, the former was kept for the purpose of crack-shear verification.

The amount of the aggregate included in 9.5-mm depth framework is illustrated in Fig. 3(a) and (b). The distribution of the aggregate in actual three-dimensional space was actually sparser than this two-dimensional illustration. Shown also in Fig. 3(c) and (d) are a typical aggregate distribution at cut sections. Compared to the aggregate amount used in typical concrete mixture, which are about 65% and 50% of γ_{max} for ordinary and self-compacting concrete mixtures, respectively, less aggregate amount was used here. This had allowed the aggregates well floated in HPFRCC matrix.

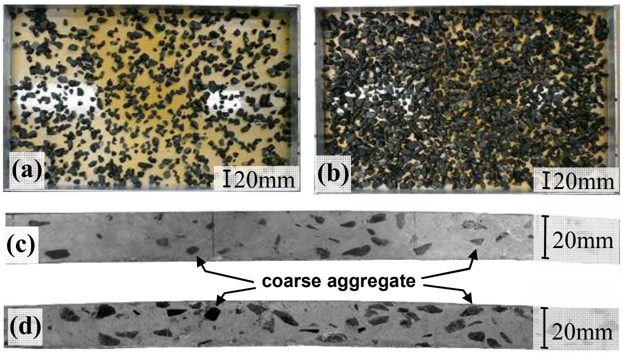

Fig.3 Illustration of aggregate used in Group 1 and Group 2 mixtures: (a), (b) in 9.5 mm depth; (c), (d) at a typical sliced section

2.3 Specimen Fabrication

The PVA-ECC mixture was prepared based on conventional procedure specified in Ref. 5. The mixture was firstly mixed for 10 minutes. Coarse aggregate was then added to the fresh mixture. It was re-mixed for about 2 minutes. To achieve uniform fiber distribution, the slurry was poured into the middle of each framework at once and shredded in a radial pattern. After two days, all specimens were demolded and kept in a controlled room at 20^{o}C and 60%RH.

Three series of specimens were fabricated, namely Group 0, Group 1, and Group 2. The Group 0 plates served as the reference specimens, which were made of original PVA-ECC mixture and contained no coarse aggregates. In this series, a new batch was re-fabricated, namely Plate 0-CR, to re-examine the first cracking load. As previously outlined, Group 1 and Group 2 plates corresponded to 30% and 15% γ_{max} coarse aggregate, respectively.

3. TEST RESULTS AND DISCUSSIONS

The first part of this section (Section 3.1) describes the result of control plates in which the influence of coarse aggregate is evaluated under increasingly monotonic loading and fixed principal tensile stress direction. The second part of this section (Section 3.2) focuses on the behavior of cracked HPFRCC in sustaining in-plane tensile and shear stresses, which also considers the effect of principal stress rotation. For this purpose, pre-cracks were introduced at tensile zone of each main plate. The result of adding coarse aggregate is again reviewed.

3.1 Control Plates Results (no pre-cracking)

Fig. 4 shows the test results for all control plates that were loaded to failure in bending. The control plates made of new mixture (1-C1, 1-C2, 2-C1, and 2-C2) showed relatively similar first cracking load to that of reference plate (0-CR), ranging from about 2.6 to 2.9 kN. The highest value was shown by the Group 1 plates, with the largest aggregate amount. This perhaps indicates the hindrance of aggregate in developing full-length crack, thereby slightly increasing the first cracking. The first cracking load of other control plates (0-C1, 0-C2) was about 1.6 kN. This large variation was likely due to the different matrix quality (e.g.: air content).

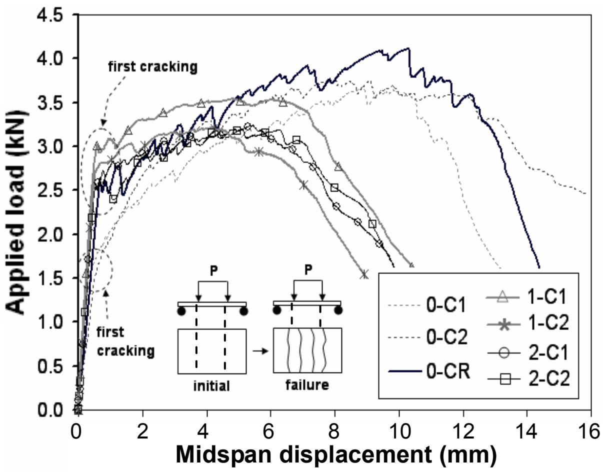

Fig.4 Load – midspan displacement of all control plates with and without coarse aggregate

The new mixture (1-C1,2 and 2-C1,2), on the other hand, showed significant reduction of strength and ductility. The ultimate strength of the plates was about 20% higher than cracking load and 20% less than that of the reference plate. The ductility, as indicated by the measured midspan displacement at ultimate, was about 5.5 mm in average, only a half to that of the reference plate.

It is not surprising that the inclusion of coarse aggregate had considerably decreased HPFRCC performance, provided that less number of fibers existed at crack sections (some parts of crack interface were now occupied by coarse aggregate). Consequently, the bridging stress margin at crack did also decrease. The fact that the new mixture still retained relatively similar cracking stress level made the situation even worse. Then, a condition that commonly stated as “unsaturated state” [4], which is characterized by the formation of less number of cracks and large variation of crack spacing, might have happened.

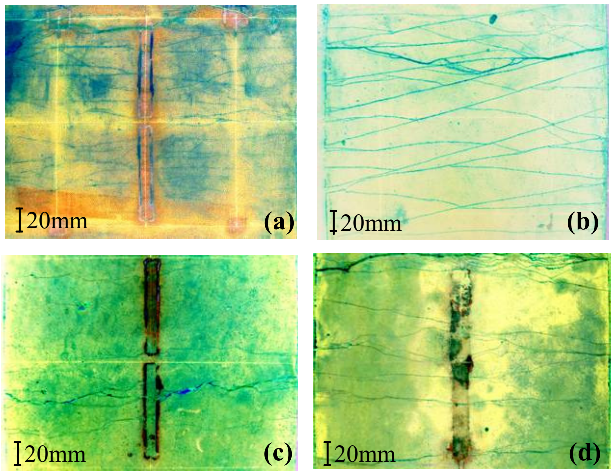

Fig.5 Typical crack pattern of control plates: (a) 0-C1, (b) 0-CR, (c) 1-C1, and (d) 2-C1

The crack pattern of control plates at failure over the inner loading span of the plate soffit are shown in Fig. 5. Generally, the more the aggregate content, the less the number of full-length cracks and the crack opening. The number of full-length cracks was decreased from about nine cracks in Group 0 [Fig. 5(b)] to six cracks in Group 2 [Fig. 5(d)] and three cracks in Group 1 [Fig. 5(c)] plates, yet with several discontinuous cracks evident. Had these micro-cracks, Plates 1-C1 and 1-C2 could thus sustain comparatively similar ductility level to those of Group 2 plates.

In general, this overall poor performance has made coarse aggregate generally be eliminated from most HPFRCC mixtures so far.

3.2 Main Plates Results (with pre-cracking)

The result of Group 0 main plates [5] is shown in Fig. 6 and again summarized in this paragraph. Pre-cracking was found to cause significant differences in the overall plate’s behavior in terms of initial stiffness, strength, and ductility. Particular attention was paid on the results of Plates 0-M45 and 0-M70, where strength reduction occurred (about 30% at worst). Negligible contribution of shear resisting mechanism was considered the trigger of this issue. This appraisal was supported by a somewhat orthogonal cracking pattern [see Fig. 8(a) to (c)]. Three likely causes of this shear deficiency were smooth crack interface (with flexible bridging fibers), breakage of some fibers due to the slippage of crack interfaces, and closely-spaced crack formation.

To gain insight into this issue, coarse aggregate was later added to the Group 1 and 2 plates, in order to improve the interface shear transfer of cracked HPFRCC.

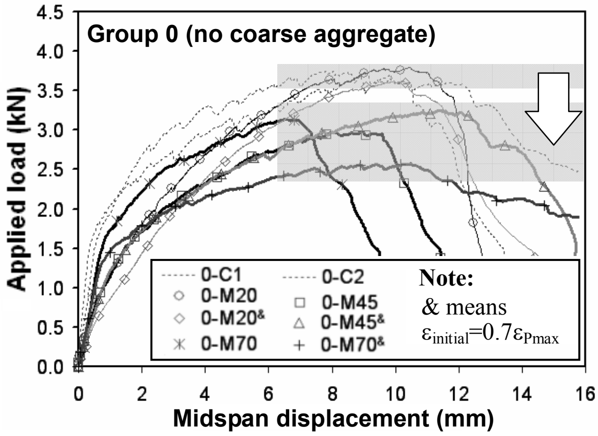

Fig.6 Load – midspan displacement of Group 0 main plates without coarse aggregate [3]

Shown in Fig. 7(a) is the load-midspan displacement of Group 1 plates. The performance of the plates in this test series, in terms of strength and ductility, was similar to their corresponding control plates (1-C1,2) and below that of the original mixture (0-CR). Significant effect of pre-cracks was observed on the early stage of the load-midspan displacement response. Like Group 0 plates, this was attributed to either opening or slip of pre-cracking. Only in Plate 1-M0 did the specimen prematurely fail due to re-opening of pre-cracks. Plates 1-M20, 1-M45, and 1-M70 showed little variation of strength and ductility, although the detailed response was somewhat different. The ductility of the plates tends to be limited at about 4 to 6 mm. Taken together, the results suggest that upgrading crack-shear interface by adding excessive aggregate amount was also ineffective. That is, only a slight bridging stress margin remained at crack, which can also be traced back to comparable level of the first cracking and the maximum load of the control plates (1-C1,2). Thus, the effectiveness of coarse aggregate at crack interface depends on the effectiveness of bridging fibers in the opening direction too.

Attempt was thus given to reduce the amount of coarse aggregate, as the Group 2 plates. The load-midspan displacement relationship of this test series is displayed in Fig. 7(b). In contrast to the results of the previous two groups, effects of pre-cracks were minor and appeared only in the early stage of Plates 2-M0 and 2-M20. This was mainly due to re-opening of the pre-cracks. The initial stiffness of Plate 2-M45 was also somewhat stiffer than that of Plates 0-M45 and 1-M45, implying less crack-shear slip and opening.

Roughly speaking, the behavior of Group 2 main plates turned to be so much ductile, becoming similar to that of Plate 0-CR. The performance of the main plates of this test series, in terms of ductility and strength, was much better than their corresponding control plates (2–C1 and 2–C2). Surprisingly, not only while shear existed at crack, for instance in Plates 1–M20, 1–M45, and 1–M70), an enhanced performance was also seen in Plates 1-M0 and 1-M90, where shear at pre-cracks were comparatively less. To understand the involved mechanism, the crack pattern of the Group 2 main

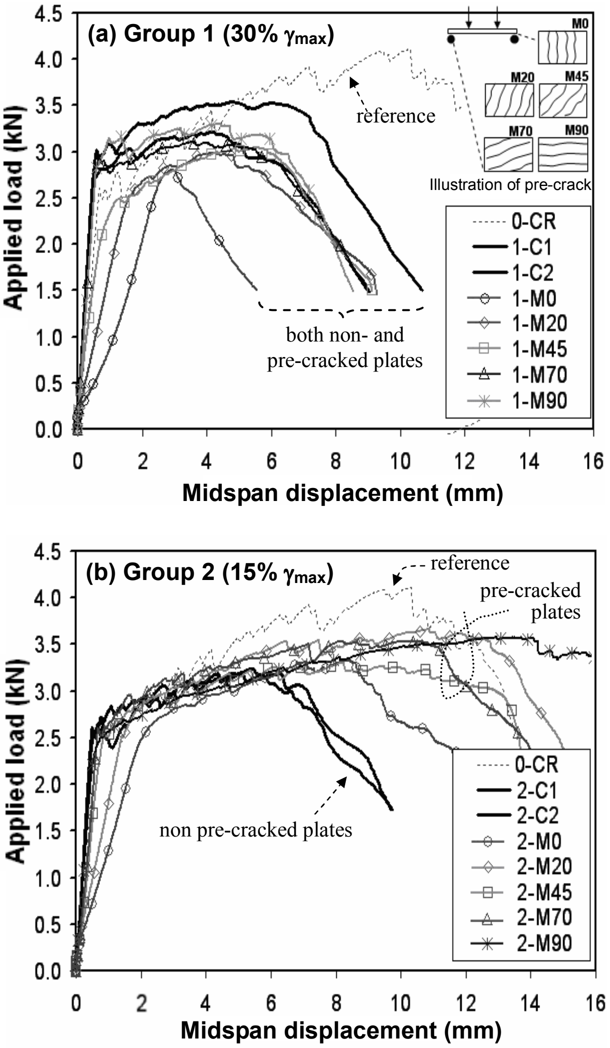

Fig.7 Results of main plates with coarse aggregate

plates is compared with the other group plates and discussed in the following paragraph.

Fig. 8 shows the typical crack pattern of main plates spanning over the inner loading span of each plate soffit, which corresponds to the hatch area in Fig. 1. In all cases, a system of crack formed, consisting pre- and secondary cracks. For Group 0 series plates [see Fig. 8(a) to (c)], the following three outlooks were observed. First, the number of pre- and secondary cracks was comparable. Although the bridging fibers of secondary-crack nearby to the pre-cracks was paralyzed (which would decrease the secondary-crack number), less strip width might also increase the potential of cracking, which would conversely increase the secondary-crack number. Thus, no major difference appeared. Second, the secondary crack was always somewhat orthogonal to the pre-crack (φ values close to 90°). As the secondary crack was the "resulting" crack, its orientation indicated the involved in-plane stress carrying mechanism. Somewhat orthogonal crack pattern here means that in-plane stress mechanism was more from those that parallel and perpendicular to the pre-crack and less from shear carrying mechanism. Three, the discontinuous pattern of the secondary crack implies the independent action of the uncracked strips in resisting tensile stress. This also emphasizes the negligible contribution of shear at crack interface.

In Group 1 plates [see Fig. 8 (d) to (g)], the number of pre- and secondary cracks was also comparable, but considerably less than Group 0 plates. This less crack number was likely related to less margin remained at crack as previously discussed. The improved shear resistance at crack interface can be actually seen from the decreased angle between the pre- and the secondary cracks (φ) for each comparative

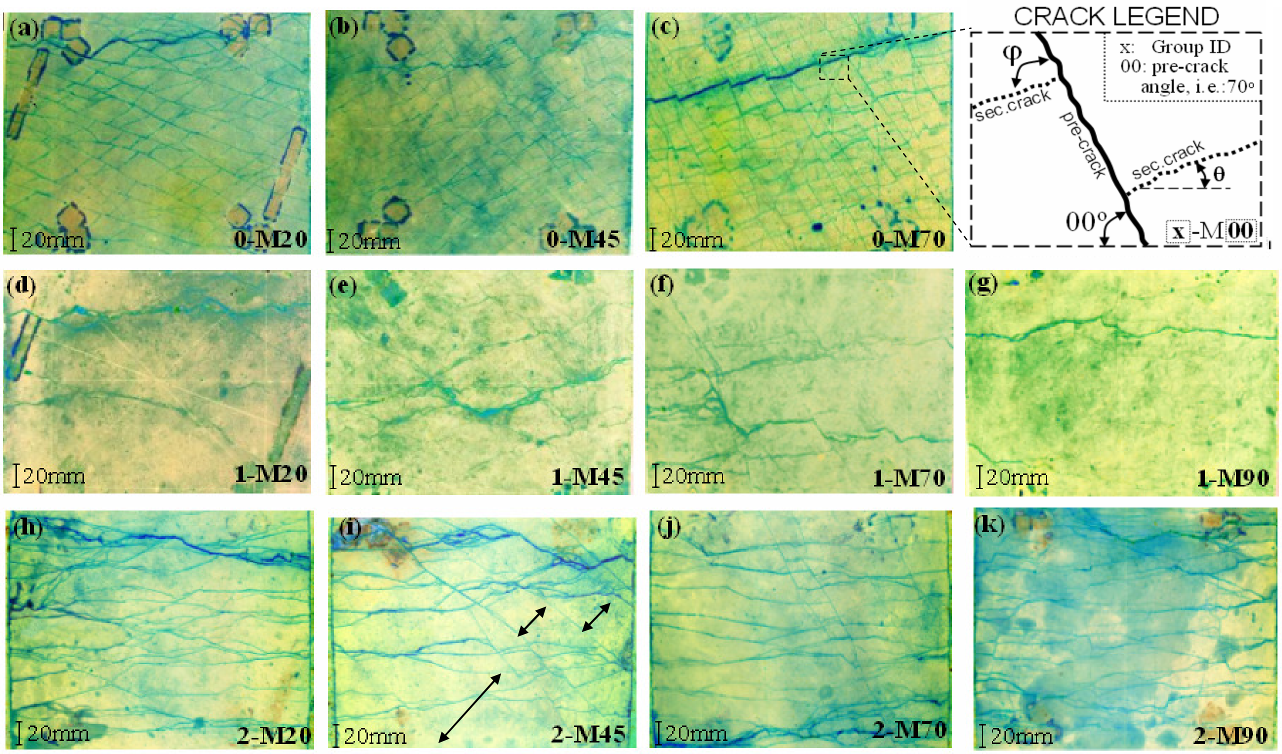

Fig.8 Crack pattern of all main plates: (a) to (c) Group 0, (d) to (g) Group 1, and (h) to (k) Group 2

pre-crack orientation, for example, 0-M20 vs 1-M20, etc. The substantial decrease of the tensile performance made the improvement of the interface shear worthless.

The number of secondary cracks in Group 2 plates [see Fig. 8 (h) to (k)] was much more than the pre-cracks. One possible reason was that pre-cracking had increased the probability of cracking; but unlike those in Group 1 plates, this advantage was well utilized with sufficient bridging fibers remained.

More importantly, anisotropic condition caused by pre-cracking tends to be nearly disappeared. The secondary cracks became accordingly less dependent to the pre-crack orientation and formed perpendicular to longitudinal direction of the plate (θ became more acute), again, the indication of more shear contribution. Furthermore, the secondary cracks were also barely arrested by the pre-cracks, leading in more continuous crack pattern. This is clearly shown by all Group 2 plates and, in particular, while comparing the secondary crack pattern of Plate 1-M90 and 2-M90. In general, the abovementioned phenomena indicated well collaboration of fibers and coarse aggregate in limiting the opening and slip of pre-cracks, thereby lowering the anisotropic effect of pre-cracking.

Detailed observation on the crack pattern of each Group 2 plate reveals a slight variety of secondary crack orientation, which was likely caused by the non-uniformity of the pre-crack spacing. This was particularly found in Plate 2-M45 [see arrow marks in Fig. 8 (i)]. On extreme, the secondary crack was somehow horizontal (θ approaches to zero) at large pre-crack spacing. The indication was that shear carrying mechanism was not solely attributable to that occurring at crack interface, but also to the uncracked matrix in between pre-cracks. Having larger crack spacing is thus beneficial for shear.

Lastly but not least, the authors would again recall the role of coarse aggregate and pre-cracking that has been verified in enhancing the performance of Group 2 plates. In existing structures, pre-cracking would inherently exist due to previous loading history and/or environmental actions. It is now the decision at hand to include coarse aggregate or not. Through this paper, it was found that the aggregate addition can result, on one hand, improving crack-shear interface, limiting the anisotropic effect of pre-cracking, increasing the potential of further cracking (with pre-cracking), potentially in protecting fibers during crack closure, and on the other hand, reducing tensile performance and hindering crack propagation (without pre-cracking). It is then important to add a proper aggregate amount to minimize its negative impacts and to maximize its positive outcomes. The role of coarse aggregate in HPFRCC might be more significant in applications without rebars. Further detailed investigations are needed to verify this proposal.

4. CONCLUSIONS

The test of pre-cracked HPFRCC plates had made us aware of the need to look more broadly the role of crack interface in sustaining not only tensile stress, but also shear stress. The test program indicated that the capability of crack interface in transferring shear was however limited. The following attempts were then undertaken:

(1) In this study, the viability to improve crack-shear interface of HPFRCC is demonstrated. Coarse aggregate, which is unfavorable in boosting HPFRCC tensile ductility, was rather added. The results showed that excessive aggregate addition resulted in inferior performance, while a suitable aggregate addition turned to a substantial performance enhancement. Out of two trials, 15% of γ_{max} gives the best result.
(2) Unlike the pre-cracked HPFRCC plates, the pre-cracked plates made of the best mixture (15% of γ_{max}) showed a stable response, which nearly resembled to that of the non pre-cracked HPFRCC plates. This enhancement was attributed to the reduced anisotropy due to the synergic collaboration of fibers and coarse aggregate, and the increasing probability of cracking.
(3) The synergic collaboration of fibers and coarse aggregate was evidently seen from the orientation of the secondary crack that became less dependent on the pre-crack orientation.

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