Pergamon

CEMENT AND CONCRETE RESEARCH

Cement and Concrete Research 30 (2000) 63–69

Development of hybrid polypropylene-steel fibre-reinforced concrete

C.X. Qian[a,*], P. Stroeven[b]

[a]Department of Materials Science and Engineering, Southeast University, Nanjing 210096, People's Republic of China
[b]Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN, Delft, The Netherlands

Received 4 October 1998; accepted 20 September 1999

Abstract

This research first investigates the optimization of fibre size, fibre content, and fly ash content in hybrid polypropylene-steel fibre concrete with low fibre content based on general mechanical properties. The research results show that a certain content of fine particles such as fly ash is necessary to evenly disperse fibres. The different sizes of steel fibres contributed to different mechanical properties, at least to a different degree. Additions of a small fibre type had a significant influence on the compressive strength, but the splitting tensile strength was only slightly affected. A large fibre type gave rise to opposite mechanical effects, which were further fortified by optimization of the aspect ratio. There is a synergy effect in the hybrid fibres system. The fracture properties and the dynamic properties will be further investigated for the hybrid fibres concrete with good general mechanical properties.

Keywords: Polypropylene fibre; Steel fibre; Concrete; Fly ash

1. Introduction

Crack growth due to loading and shrinkage should both be controlled in slablike concrete structures, such as pavements, runways for airports, and continuous slab-type sleeper for high-speed trains. In these types of structures, effective prestressing for crack control purposes will be very difficult, especially in the two principal directions. So, dispersed short fibre reinforcement offers a second approach in this case.

It has been shown earlier [1–3] that cracking resulting from shrinkage and differential settlements during the fresh state can be effectively inhibited by a monofilament type of polypropylene fibre reinforcement (PP). Because of the large numbers involved, fibres can be properly distributed throughout the mortar matrix, around the coarse aggregate particles, and even in boundary layers of concrete elements. The PP fibre has a low Young's modulus, however. As a consequence, they cannot prevent the formation and propagation of cracks at high stress level. Neither can they bridge large cracks.

Steel fibres have a considerably larger length and higher Young's modulus as compared to the PP fibre. This leads to an improved potential for crack control. But volumetric density is high, and steel is conductive in electric and magnetic fields. So, steel fibre content has to be reduced to below a certain level in structures such as tunnels and continuous slabs for high-speed railway systems, where the communication system can be disturbed. Optimization of mechanical and conductivity properties can be achieved by combining different kinds, types, and sizes of fibres, such as in case of PP and steel fibres according to Bentur and Mindess [4] about the attractive advantages of hybrid fibre systems:

1. To provide a system in which one type of fibre, which is stronger and stiffer, improves the first crack stress and ultimate strength, and the second type of fibre, which is more flexible and ductile, leads to improved toughness and strain capacity in the post-cracking zone.
2. To provide a hybrid reinforcement, in which one type of fibre is smaller, so that it bridges microcracks of which growth can be controlled. This leads to a higher tensile strength of the composite. The second type of fibre is larger, so that it can arrest the propagating macrocracks and can substantially improve the toughness of the composite.
3. To provide a hybrid reinforcement, in which the durability of fibre types is different. The presence of the durable fibre can increase the strength and/or toughness retention after age while another type is to guarantee the short-term performance during transportation and installation of the composite elements.

* Corresponding author. Tel.: +86-25-379-4392; fax: +86-25-771-2719.
E-mail address: cxqian@publicl.ptt.js.cn (C.X. Qian)

PII: S0008-8846(99)00202-1

Table 1
Physical characteristics of fly ash

Density	Loss on ignition	45-μm sieve residue	Moisture content
2.248 g/cm^3	3.63%	14.92%	0.11%

Table 2
Aggregate gradations (taking 0.125–16 mm particles as 100%)

	Particle size (mm)							
	0.125–0.250	0.250–0.5	0.5–1	1–2	2–4	4–8	8–16	0.125–4
Content (%)	3	11	11	10	10	25	30	45

This research concentrates on strong steel fibres combined with PP fibres and on large steel fibres used in combination with the smaller one. The fibre contents are in the low range (i.e., steel fibre volume content up to 1.2% and PP fibre up to 0.3%). This paper is the first part of the research. It mainly deals with the proper aggregate gradation, the minimum cementitious materials content, the proper combination of fibre sizes, and contents based on the general properties of the hybrid fibre concrete under static loading. The fracture properties of the hybrid fibres concrete will be reported in another paper.

2. Materials and methods

2.1. Materials

1. A Portland cement type C of Dutch origin, but equivalent to ASTM C 150 Type I, was used in this study; the characteristic strength amounted to 52.5 MPa. The 45-μm sieve residue was 3.22%.
2. An ASTM C 618 Class F fly ash was used as a mineral admixture. The physical characteristics are listed in Table 1. The density was tested according to Dutch recommendations that are similar to ASTM C 188. Loss on ignition and moisture content were measured according to ASTM C 311. The 45-μm sieve residue was determined in accordance with ASTM C 430.
3. A monofilament type of PP fibre with a length of 12 mm and a diameter of 18 μm was employed.
4. Three types of steel fibres were used. Type SF1 is hooked steel fibres with a length of 40 mm and a diameter of about 0.3 mm. Type SF2 is hooked steel fibres with a length of 30 mm and a similar diameter of about 0.3 mm. Type SF3 is high-strength plain steel fibre with a length of 6 mm and a diameter of 0.1 mm at the most.
5. A melamine-based superplasticizer with a solid content of 35% was used. Maximum dosage amounted to 3.0% by weight of the cement.

2.2. Experiments

The concrete strength grade of 60 MPa on which this research was based was designed according to Shui and Stroeven [5] on a water-cement ratio of 0.40 and a cement content of 400 kg/m^3. A different content of fly ash was added to obtain a dense matrix in which the fibres were evenly distributed. The gradation of the aggregate given in Table 2 is selected according to trial experiments documented previously [6].

The mixing procedure for fresh concrete mixtures is shown in Fig. 1. Table vibration time was 24 s for fresh mixtures with a slump of more than 160 mm and 48 to 60 s for low-slump mixtures. The specimens were stored at 23 ± 3°C and 95 to 100% relative humidity for about 24 h, whereupon they were carefully demoulded. The 1-day compressive strength was determined as a reference for prestressing purposes. The rest of the specimens were re-stored under the same conditions until the day of testing. The 1-day compressive strength (f_{cc}, 1 day) and the 28-day compressive strength (f_{cc}, 28 days), splitting (tensile) strength (f_{spl}), and central-point modulus of rupture (MOR) are experimental parameters used in this research for the assessment of the fibre effect. Cubes of 150 mm were used for compression and splitting tension testing. Prisms (100 × 100 × 400

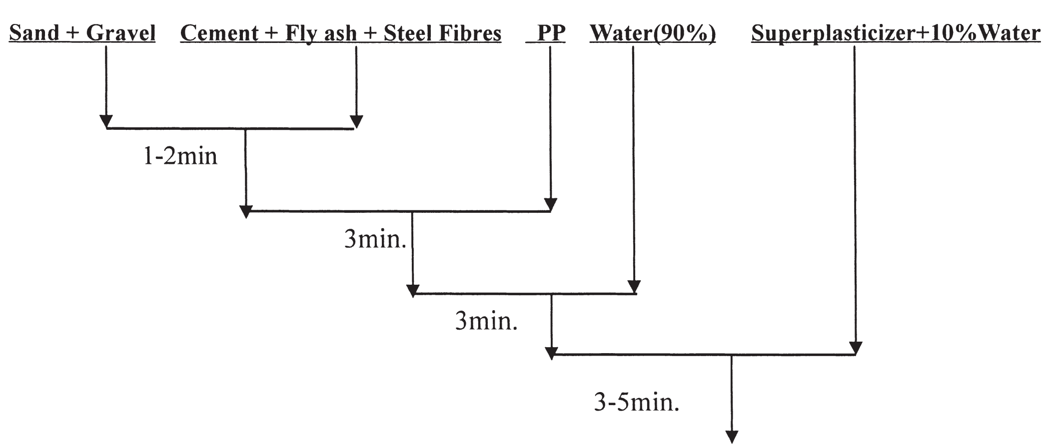

Fig. 1. Mixing procedure for fresh concrete mixtures.

Table 3
Hybrid fibre concrete with different content of fly ash

Mix no.	Fly ash (kg/m^3)	Superplasticizers (%)	Fibre content (%, by volume of concrete)				
			PP	SF1	SF2	SF3	Total
F11	100	2.5	0.3	0	0.2	0.4	0.9
F51	50	2.5	0.3	0	0.2	0.4	0.9
F01	0	2.5	0.3	0	0.2	0.4	0.9
F12	100	2.5	0.15	0.2	0.2	0.2	0.75
F52	50	2.5	0.15	0.2	0.2	0.2	0.75

Table 4
Orthogonal arrays for four factors and three levels

Mix no.	PP (%)	SF1 (%)	SF2 (%)	SF3 (%)	Total (%)	Superplasticizers (%)
1	(1) 0.15	(1) 0	(1) 0	(1) 0	0.15	2.5
2	(1) 0.15	(2) 0.2	(2) 0.2	(2) 0.2	0.75	2.5
3	(1) 0.15	(3) 0.4	(3) 0.4	(3) 0.4	1.35	2.5
4	(2) 0.30	(1) 0	(2) 0.2	(3) 0.4	0.90	2.5
5	(2) 0.30	(2) 0.2	(3) 0.4	(1) 0	0.90	2.5
6	(2) 0.30	(3) 0.4	(1) 0	(2) 0.2	0.90	2.5
7	(3) 0	(1) 0	(3) 0.4	(2) 0.2	0.60	1.0
8	(3) 0	(2) 0.2	(1) 0	(3) 0.4	0.60	1.0
9	(3) 0	(3) 0.4	(2) 0.2	(1) 0	0.60	1.0

mm) with a span of 300 mm were employed for determination of MOR in central-point loading. The broken pieces were then tested in splitting tension at sections 50 mm from the ends of the original prism. This splitting strength value is denoted by f_p. The splitting plane is the vertical central section of the cube or the vertical section of the prism. The cube or the prism is turned over 90° with respect to casting direction.

The concrete specimens with different content of fly ash as shown in Table 3 are designed to investigate the effect of fly ash.

Other testing was performed on the basis of a statistical design in which the various fibre types, sizes, and contents were incorporated. A series of four factors and three levels were envisaged, as presented in Table 4. Monofibre concrete mixtures and plain ones served as reference, as specified in Table 5. The dosage of superplasticizer for mix no. 1–6 is 2.5% and is 1.0% for mix no. 7–9.

Table 5
Concrete mixtures with monofibre or without fibre

Mix no.	PP (%)	SF1 (%)	SF2 (%)	SF3 (%)	Total (%)	Superplasticizers (%)
10	0	0	0	0	0	1.0
11	0.3	0	0	0	0.3	2.5
12	0	0	0.9	0	0.9	2.5

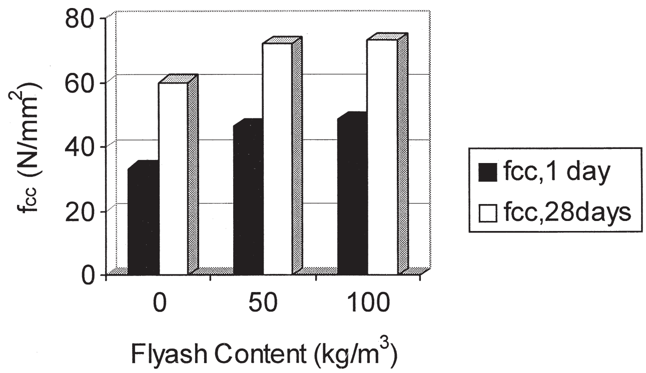

Fig. 2. Influence of fly ash content on f_{cc} of concrete with hybrid fibres (F11, F51, F01).

3. Results and discussion

3.1. Effect of fly ash on hybrid fibre concrete

The effect of fly ash content on the general properties of hybrid fibre concrete is shown in Figs. 2 and 3. It can be seen that 50 to 100 kg/m^3 of fly ash is necessary for hybrid concrete to obtain better static properties, which is also a reference of microstructure of the concrete. The higher the strength, the denser the structure is as the fibre content is the same.

One cube of 150 mm for each mixture was prepared and cut along the center of the vertical section to investigate the dispersion of fibres. The results show that PP and the steel fibres dispersed evenly in the concrete containing fly ash. Figs. 4a and b show quantitatively the dispersion of steel fibres in the concrete containing 0.15% of PP, 0.40% of SF1, 0.40% of SF3, and 100 kg/m^3 of fly ash. The vertical section of the cube was divided into 10 strips from top to bottom, from side one to side two, respectively. The fibres in each strip (10 × 150 mm) were counted.

3.2. Optimization of steel fibre content and type

The optimization of the fibre content and the fibre type was first carried out based on the compaction capacity of fresh mixture and the static properties. Those properties

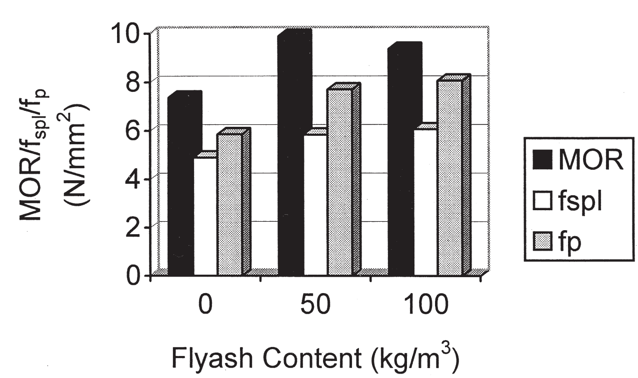

Fig. 3. Influence of fly ash content on MOR and splitting strength of hybrid fibres concrete (F11, F51, F01).

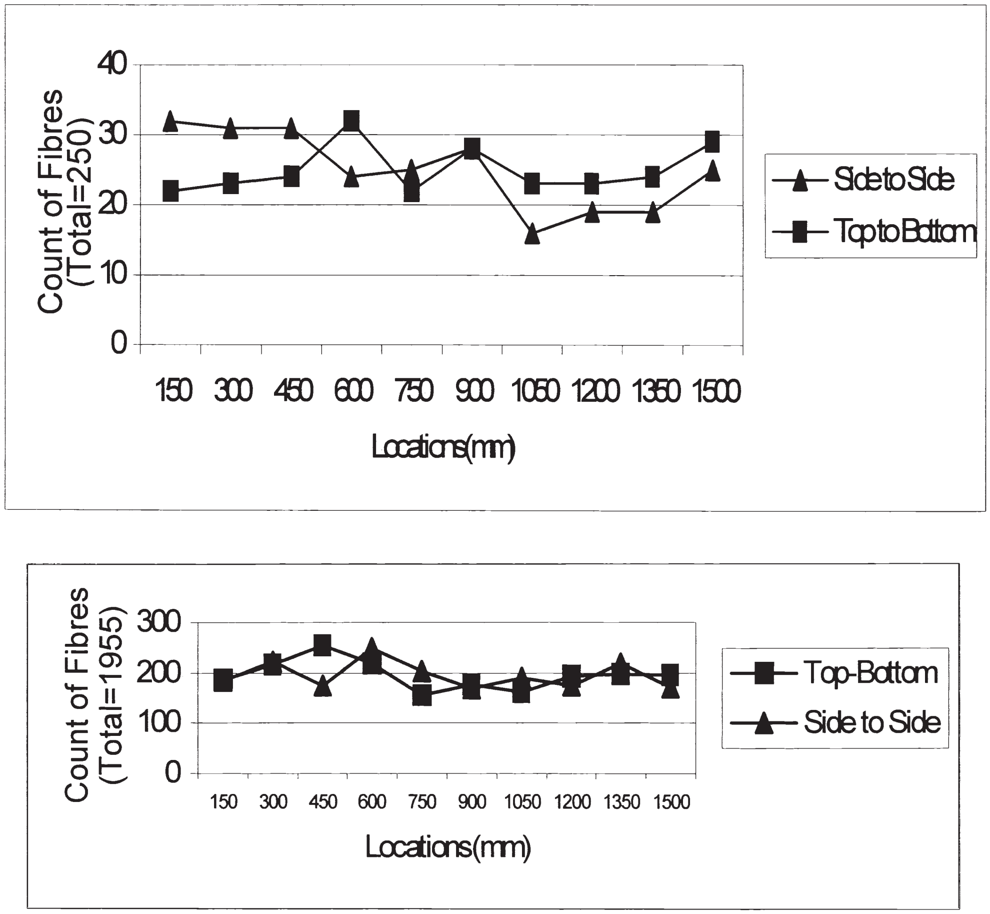

Fig. 4. (top) Distribution of large fibre SF1. (bottom) Distributions of small fibre SF3.

should be also acceptable for high performance hybrid fibres concrete with high capacity on crack arresting. The hybrid fibre concrete with acceptable static properties will be further investigated in other aspects in the future. The unit weight, the compressive and splitting tensile strengths, and the modulus of rupture from this first research stage are listed in Table 6. The values in brackets are variations.

The data in Table 6 have been subjected to a statistical analysis to see whether observed effects were significant. As a first step, a maximum difference analysis has been executed according to Chai and Wang [7]. The following classification of average differences of fibre effects can be made:

f_{cc}, 28 days: PP > SF3 > > SF1 > SF2
MOR: SF1 ≅ SF3 > PP > > SF2
f_{spl}: SF1 > PP > > SF2 ≅ SF3
f_p: SF1 > SF2 > > PP ≅ SF3

The maximum difference analysis allows classification of the average effects of various parameters in a simple and obvious way. It does not consider experimental scatter, al-

Table 6
Properties of hybrid fibre concrete

Mix no.	Unit weight (kg/m^3)	f_{cc}, 1 day (MPa)	f_{cc}, 28 days (MPa)	MOR (MPa)	f_{spl} (MPa)	f_p (MPa)
1	2,395	43.6 (0.7)	71.2 (4.3)	8.76 (0.38)	5.28 (0.12)	6.14 (0.16)
2	2,421	44.5 (0.2)	73.6 (0.7)	9.53 (0.38)	6.20 (0.04)	8.27 (0.44)
3	2,463	47.4 (0.7)	82.8 (3.7)	12.66 (0.18)	8.01 (0.39)	10.35 (0.52)
4	2,428	48.6 (0.5)	73.0 (6.0)	9.37 (0.26)	6.06 (0.22)	8.06 (0.57)
5	2,404	36.1 (0.2)	67.9 (6.2)	8.49 (0.25)	6.34 (0.21)	9.19 (0.52)
6	2,417	43.0 (1.2)	72.2 (2.9)	9.98 (0.57)	6.16 (0.38)	8.60 (0.64)
7	2,438	34.4 (0.8)	58.8 (3.0)	8.47 (0.13)	4.93 (0.16)	7.02 (0.67)
8	2,433	46.6 (0.4)	72.8 (2.2)	9.12 (0.52)	5.43 (0.14)	7.78 (0.34)
9	2,435	41.0 (2.3)	61.4 (4.8)	9.04 (0.62)	5.86 (0.21)	8.48 (1.01)

Table 7
Test results of single samples

	f_{cc}, 28 days (MPa)			MOR (MPa)			f_{spl} (MPa)			f_p (MPa)			
Mix no.	1	2	3	1	2	3	1	2	3	1	2	3	4
1	66.3	73.1	74.1	8.78	8.37	9.14	5.17	5.41	5.27	6.37	6.05	6.08	6.04
2	73.6	72.9	74.2	9.81	9.09	9.68	6.19	6.24	6.16	8.10	7.77	8.41	8.79
3	82.0	86.9	79.6	12.82	12.69	12.46	8.21	8.27	7.56	10.31	9.71	10.99	10.38
4	75.5	66.1	77.3	9.22	9.68	9.22	5.82	6.24	6.11	7.45	8.03	8.82	7.93
5	61.8	74.2	67.8	8.37	8.32	8.78	6.10	6.43	6.48	9.56	8.44	9.52	9.24
6	70.5	75.6	70.7	10.58	9.45	9.90	6.06	6.58	5.83	9.30	7.80	8.41	8.89
7	55.6	61.3	59.6	8.55	8.55	8.32	4.77	4.94	5.08	7.52	6.53	7.68	6.37
8	70.8	75.1	72.5	8.64	9.04	9.68	5.58	5.32	5.38	7.59	8.23	7.58	8.09
9	56.0	62.8	65.2	8.50	8.91	9.72	5.87	6.06	5.64	7.93	9.43	9.21	7.33

though the experiments were done very carefully. To separate signal from scatter, a variance analysis should be performed. Two scatter sources can be distinguished: between-group scatter, which is due to variation among data of similar experiments pertaining to different batches of the same mixture, and in-group scatter, which results from variation among experimental observations on specimens of a single mix. The in-group scatter is the smaller of the two. In this research, a group of three or four specimens were prepared from a single batch only. Thus, only the in-group scatter is taken into consideration in this stratified sampling scheme. The variance analysis is based on the test results of single samples listed in Table 7, and performed in accordance with previous work [8–10].

The variance analysis allows a classification of the parameters on the basis of significance:

f_{cc}, 28 days: PP $>$ SF3 $>>$ SF1 $\cong$ SF2
MOR: SF1 $>$ SF3 $>$ PP $>>$ SF2
f_{spl}: SF1 $>$ PP $>>$ SF3 $\cong$ SF2
f_p: SF1 $>>$ SF2 $>>$ SF3 $\cong$ PP

The classification results of the variance analysis support those of the maximum difference analysis. The effects of both PP and SF3 on f_{cc} are significant (i.e., the free degree F value exceeds the $F_{0.01}$ value considerably). Therefore, the influence of PP and SF3 on f_{cc} is not caused by experimental variance. This also holds for the influences of PP, SF1, and SF3 on MOR and for SF1 and SF2 on f_p. For detailed analysis process and results, refer to previous work [11].

In summary, the following conclusions can be drawn as to the various steel fibres. The small fibres of SF3 give rise to considerable effects on f_{cc} and MOR, but not on f_{spl} and f_p. Contrary, the large fibres of SF1 yield only very small effects on f_{cc}, but yield considerable influence on MOR, f_{spl}, and f_p because of the larger aspect ratio. According to these results, the optimized hybrid fibre system should be composed of PP, SF1, and SF3 as both compressive and tensile loading are considered.

3.3. Optimization of PP fibre content

Experimental data on mechanical properties of PP fibre-reinforced concrete are presented in Fig. 5. These monofibre concretes reveal 0.15% to be the optimum fibre content. Only the MOR seems somewhat improved by raising the fibre content to 0.3%.

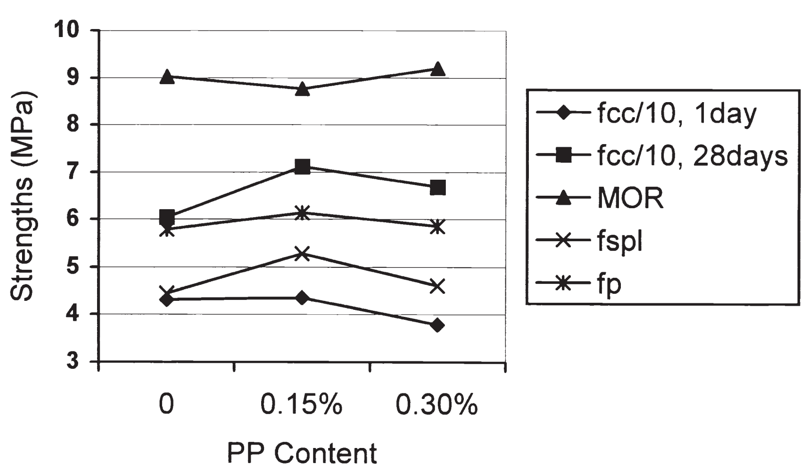

Fig. 5. Influence of PP content on concrete properties.

3.4. Comparison of hybrid fibre system with monofibre system

Fig. 6 shows the comparison between monofibre system and hybrid fibre system. Mix 10 is plain concrete. Mix 12 is the concrete reinforced with 0.90% monofibre SF2. Mix 6 is the concrete reinforced with 0.30% PP, 0.40% SF1, and 0.20% SF3. Its total fibre content is 0.90%. Mix 2 is the concrete reinforced with 0.15% PP, 0.20% SF1, 0.20% SF2, and 0.20% SF3. Its total fibre content is 0.75%. The "average" in Fig. 6 means the average of $f_{cc}/10$ (28 days), MOR, f_{spl}, and f_p. It reflects the general state of those four parameters. It can be seen from Fig. 6 that the value of the "average" of mix 2 is close to that of mix 12 even though the fibre content of the former is less than that of the latter. This shows the advantage of hybrid fibre system. The properties of the hybrid fibre system mix 6 would be better than that of monofibre system mix 12. But it is only similar to mix 12 because the PP content in mix 6 is higher than optimum value. The hybrid fibre system of 0.15% PP (optimum), 0.40% SF1, and 0.20% SF3 must be better than mix 6.

3.5. Mechanisms and micromechanics

A strengthening and a weakening effect are the opposite results of adding fibres to concrete [12,13]. Fibres strengthen the matrices not only because they carry part of the applied load, but also (far more important) strengthen the matrices by their crack- and pore-bridging capability. The resulting mechanism of crack control leads to a delay of failure. This implies that even low-modulus fibres, such as PP, have the ability to strengthen brittle cementitious materials. This is the reason that the PP fibre turned out to be a significant factor among those governing the static mechanical properties of hybrid fibre concretes, as studied in this research.

An excess of fibres may have adverse effects on strength due to the introduction of additional defects during the processing stage [12,14]. Hence, the optimum packing stage of particles and fibres cannot be achieved. This is why the concrete properties were reduced after the PP content was increased from 0.15 to 0.3% in this research.

The different sizes of steel fibres exerted different mechanical responses in the present research. It was observed during execution of the compression test in the present research that audible noise due to cracking was produced before arriving at ultimate loading; a phenomenon detected earlier by application of an acoustic emission technique under similar conditions [15]. Obviously, damage evolution is already significant in the prepeak range. During compression test of fibre concretes, the scale of the test machine even stopped a while before moving toward the ultimate load level. This behaviour was also found in splitting tension but not in bending.

Hence, fibres allowed for redistribution of the load-bearing capacity during this process of preultimate damage evolution. At termination of bending and splitting tensile tests, all samples of fibre concrete consisted of two parts still connected by fibres bridging the major crack. Thus, the micromechanical feature of crack bridging is operative from early stages of damage evolution to beyond ultimate loading. In contrast, the plain concretes and those reinforced by only 0.15% of PP fibres were completely separated at ultimate loading.

4. Conclusions

High performance hybrid fibre concrete should first possess good capacity on compaction and static properties, such as compressive strength, MOR, and splitting strength. Therefore, this research first investigates the optimization of cementitious matrix, fibre type, and fibre content based on previously mentioned properties. Further research will discuss the fracture properties and impact properties of the hybrid fibre concrete with good static properties. The following results about the development of hybrid fibre concrete can be obtained.

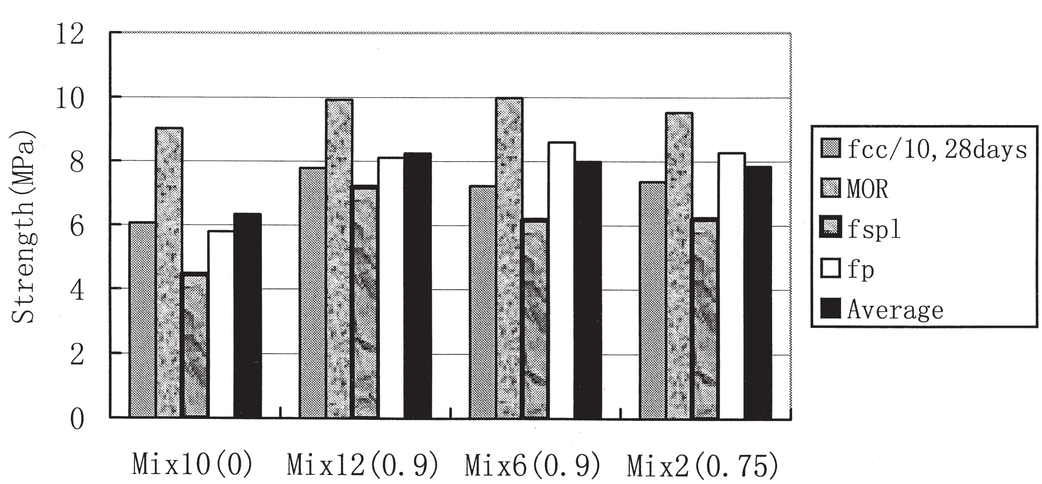

Fig. 6. Comparison of hybrid fibre system and monofibre system.

- A certain content of fine particles such as fly ash is necessary to evenly disperse the hybrid fibres containing ultra-fine polypropylene fibres.
- The optimum dosage of PP fibre was 0.15% under 400 kg/m^3 cement and 100 kg/m^3 fly ash in concrete. The weakening effect of incomplete densification of the cementitious matrix did outweigh the effect of a heavier reinforcement at a higher dosage.
- The different sizes of steel fibres contributed to different mechanical properties, at least to a different degree. Additions of a small fibre type had a significant influence on the compressive strength, but the splitting tensile strength was only slightly affected. A large fibre type gave rise to opposite mechanical effects, which were further fortified by optimization of the aspect ratio. This effect of (steel) fibre size is due to the different cracking densities provoked by the different testing modes.
- PP, SF1, and SF3 consist of a satisfactory hybrid fibre system compared with SF2 in low fibre range in which the total fibre content is lower than 1.0%.
- The synergy effect implemented in a hybrid fibres system (mix 2) was found to lead to similar significant improvements that could be realized with a monofibre system having the higher total fibre content (mix 12), provided the different types and sizes of fibres were properly dispersed.

Acknowledgments

The authors gratefully acknowledge the financial support from Royal Dutch Academy of Science.

References

[1] M.A. Sanjuan, C. Andrade, A. Bentur, Effect of crack control in mortars containing polypropylene fibres on the corrosion of steel in a cementitious matrix, ACI Materials Journal 94 (2) (1997) 134–141.

[2] K. Kovler, J. Sikuler, A. Bentur, Free and restrained shrinkage of fibre reinforced concrete with low polypropylene fibre content at early age, in: R.N. Swamy (Ed.), Fibre Reinforced Cement and Concrete, E&FN Spon, London, 1992, pp. 92–101.

[3] H. Krenchel, S.P. Shah, Restrained shrinkage tests with polypropylene fibre reinforced concrete, in: S.P. Shah, G.B. Baston (Eds.), Fibre Reinforced Concrete and Applications, American Concrete Institute SP-105, Detroit, 1987, pp. 141–158.

[4] A. Bentur, S. Mindess, Fibre Reinforced Cementitious Composites, Elsevier Applied Science, London, UK, 1990.

[5] Z. Shui, P. Stroeven, Optimization of fracture mechanical behavior of low content hybrid fibre reinforced concrete, Technical Report 03.21.1.32.20, Faculty of Civil Engineering, Section of Mechanics and Structures, Delft University of Technology, September 1997.

[6] C.X. Qian, P. Stroeven, Optimization of hybrid polypropylene-steel fibres reinforced concrete, Technical Report 03.21.1.32.13, Delft University of Technology, The Netherlands, August 1998.

[7] Z. Chai, Z. Wang, Application of Orthogonal Design in Concrete Research (in Chinese), Chinese Building Industry Press, Beijing, 1985.

[8] S. Ghosh, Statistical Design and Analysis of Industrial Experiments, Marcel Dekker, Inc., New York, 1990.

[9] A. Garcia-Diaz, D.T. Phillips, Principles of Experimental Design and Analysis, Chapman & Hall, London, UK, 1995.

[10] R. Mead, The Design of Experiments: Statistical Principles for Practical Applications, Cambridge University Press, Cambridge, UK, 1988.

[11] C.X. Qian, P. Stroeven, General properties of concrete reinforced with polypropylene-steel hybrid fibres, Technical Report 03.21.1.32.14, Delft University of Technology, The Netherlands, August 1998.

[12] V.C. Li, H. Mihashi, H.C. Wu., Micro-mechanical model of mechanical response of HPFRCC, in: A.E. Naamam, H.W. Reinhardt (Eds.), High Performance Fibre Reinforced Cement Composites 2, E & FN Spon, London, U.K., 1996, pp. 43–100.

[13] B. Cotterell, Y.W. Mai, Fracture Mechanics of Cementitious Materials, Lackie Academic & Professional, Glasgow, UK, 1996.

[14] P. Stroeven, R. Babut, Fracture mechanics and structural aspects of concrete, Heron 31 (2) (1986) 15–44.

[15] A.T. Moczko, D.H. Dalhuisen, P. Stroeven, Acoustic emission and mechanical behaviour of concrete subjected to deformations from the inside, in: A. Bakker (Ed.), Symp. of the 7th International Conference on Mechanical Behaviour of Materials, The Hague, May 28–June 2, 1995, pp. 603–604.