Effect of different sizes and contents of thin and short fibres on flexural strength of high-ductile mortar

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Abstract

Flexural strength of high-ductile mortar (HDM), with Polyvinyl Alcohol fibres, depends upon the material selections, mix proportions, mixing method and casting procedure. High-ductile mortar should have higher flexural strength with its high deformation behaviour. Author carried out experimental work to identify the appropriate size, combination and content of Polyvinyl Alcohol fibres required for HDM. Three types of fibres as RMH182 ($\phi 14 \mu\text{m} \times 6 \text{ mm}$), REC15 ($\phi 40 \mu\text{m} \times 12 \text{ mm}$) and RECS100 ($\phi 100 \mu\text{m} \times 12 \text{ mm}$) were used in the experiment. The flexural strength of 9.01 MPa was obtained from the mortar with 1.5% (by volume) of RMH182 fibre. Those values were 8.65 MPa and 8.01 MPa from the mortar with 2% of REC15 and RECS100 fibres, respectively. The use of 2% of REC15 fibre gave higher flexural strength (9.5 MPa) than that from the combination of 1% of REC15 and 1% of RECS100 fibres (9.1 MPa). It was concluded that the thinner fibre gives the higher flexural strength than from the thicker one, and the single size fibre is better than the combination of two different types.

Keywords High-ductile mortar · Polyvinyl alcohol fibres · Single size fibre · Combination of different fibres · Flexural strength

1 Introduction

Concrete is one of the most popular materials used to construct civil infrastructures, due to its availability, low cost, flexibility of handling and being able to shape into any desired form. However, concrete is also one of the most difficult materials to manage, because it is a mixture consisting of cement, water, sand, gravel and other aggregates [1].

With modernization on concrete design and construction work, many attempts have been made and implemented to develop different types of concrete required for different structural performances. Initiation for the development of Self-Compacting Concrete (SCC) was started in the University of Tokyo, Japan, in mid 1980s, with the target of reducing durability problems in heavily and complicated reinforced structures due to lack of skilled

workers and a poor communication between designers and construction engineers [2]. The concept of SCC was developed by Okamura, and his guidance; the prototype SCC was developed by Ozawa [3, 4]. Wille et al. [5] developed the ultra-high-strength concrete with the compressive strength exceeding 200 MPa.

Among different types of concrete, fibre-reinforced cements and concrete (FRC) are firmly established as construction materials. Since the early 1960s, extensive research and developments have been carried out with FRC materials leading to a wide range of practical applications [6]. The interrelation of the structural performance of FRC with material constituents, processing and mechanical properties was proposed by Prof. Victor Li [7]. According to his model, the processing is one of the most important factors to create the action of coating, dispersion, orientation and resulting in good quality. These are directly related to

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the structural application of FRC through its mechanical properties.

With regard to the production of FRC, many trials had been carried out, especially with the timing of adding fibre materials when mixing and other materials as well. American Concrete Institute had listed the five methods of adding fibre materials in 1982 [8].

However, American Concrete Institute, ACI 6.44-3R (1993), has indicated that the fibres should be added to a fluid mix, either as the last stage of mixing or added to the mixer with the aggregates [9]. Both documents of ACI indicated that care should be taken to avoid fibre balling. Many recommendations were made such as to avoid the clumps of fibre adding and slow rate of adding to allow dispersion.

Bartos and Hoy [10–12] had studied about the effect of mixing procedure on the properties of fibre-reinforced concrete and especially with the feeding sequence of ingredients into the mixer. The method of adding water and the time of adding fibres affected different properties of concrete in different ways. The best charging sequence may therefore depend on the performance criteria adopted, which depends upon the specific application requirements. The mixer used should be designed to prevent any fibres becoming lodged in gaps between the mixing blades or the mixing container. One of the most significant forecasts they made in their research was that ordinary mixers, recently used in construction practice, may not satisfy the above-mentioned requirement to obtain better quality of mixed FRC [11, 12].

Japan Concrete Institute [13] has recommended that the mixing of concrete should be followed by feeding of fibre materials.

Synthetic fibres have become more attractive in recent years as reinforcements for cementitious materials. This is due to the fact that they can provide inexpensive reinforcement for concrete, and if the fibres are further optimized, greater improvements can be gained without increasing the reinforcement costs [14]. Moreover, unlike the steel fibre, which is highly corrosive in nature, there is no corrosion concern regarding synthetic fibres in concrete.

Victor Li, in early 1990s, first introduced that inclusion of small and thin synthetic fibres in cementitious material enhances toughness and increases crack resistance capacity as well as damage resistance capacity. His proposed product was known as Engineered Cementitious Composites (ECC) [14, 15]. By the time, Kuraray was the first Japanese company to develop Polyvinyl Alcohol (PVA) fibres. PVA fibres have high tenacity, high modulus, low elongation, light weight, good resistance against chemicals (alkaline) and good adhesion to cement matrix [16]. PVA fibres act greatly in a cement-based matrix with no

coarse aggregates due to their surface formation and high strength. The resulting composite, which exhibits a pseudo-ductile behaviour, is called ECC [14, 15].

Gong and Zhang carried out the research work about the effect of PVA fibre diameter on the crack resistance properties of ECC. They showed that using high performance fibre-reinforced cementitious composite (HPFRCC) materials, instead of normal concrete in RC frames, increased the ultimate load, ultimate deflection, ductility ratio and plastic hinge characteristics of the frames [17].

Zhang et al. showed from their experimental work that as the W/C varies from 0.35 to 0.25, both bending strength and ductility have a sudden change. When W/C is higher than 0.35, the influence of W/C on the bending strength and the ductility is smaller than that when W/C is lower than 0.35 [18].

Pang et al. [19] showed from their experiments that the fly ash content, ratio of binder to sand and curing condition have an influence on the tensile properties of the high-ductility cementitious composites (HDCC). The tensile strain increases with the increase in fly ash content and the decrease in sand content. For the matrix with relative high crack toughness, the ultimate tensile strain of the HDCC is smaller, but the large strain can be maintained with the tardily descending stress.

Li and Xu [20] showed that the theoretical analysis and experimental results both indicate that the proposed toughness index is independent of depth for strain-hardening cementitious composite, which can be considered as an intrinsic material property.

Jute fibre-reinforced cementitious composites (JFRCC) mortar panels did not shatter into pieces and demonstrated a ductile failure, while the plain mortar ones behaved very brittle and shattered into pieces. The impact resistance, in terms of the number of impact blows survived and the total energy absorbed upon failure, of JFRCC mortar panels decreased with age [21].

Wang et al. [22] found that the higher compressive strength and greater toughness of cement-based composites, as well as the presence of strong coarse aggregate and fibres, contribute positively to the impact resistance of composites.

Zhang et al. [23] showed that the dynamic performance of polypropylene fibre-reinforced mortar (PFRM) is significantly affected by strain rates. Nevertheless, the strain rate effect decreases as the strength of mortar increases. Polypropylene fibres are able to improve the impact toughness.

Theoretically, we know that if small and thin fibres are uniformly distributed and if each individual fibre is well coated with mortar, then it is possible to increase the strength and ductility of mortar by strengthening the transition zone in between paste and aggregate as

each well-coated fibre plays the important role of structural bridging the phases. For this, small and thin fibres were predistributed before mixing with mortar. Moreover, sequence and timing of charging each ingredient were modified while mixing fibre mortar. The result was obtained:

- (1) Predistribution of PVA fibres in air pressure gave the best result of the distribution [24].
- (2) Mixing of fibre mortar in chopper mixer gave the better result than in a mortar mixer [24].

A new mixing method, High-Ductile Mortar (HDM) mixing method, was developed in order to disperse the thin and short PVA fibres and coated each fibre firmly with mortar. The newly developed HDM mixing method enhanced both the flexural strength and deformation behaviour of the HDM [25].

With the use of this new HDM mixing method, the author hereby has attempted to choose the parameters as size, combination of different sizes and content of PVA fibres in order to investigate the flexural strength of HDM

1.1 Objective

The main aim of this experimental and investigative work was to identify the appropriate size, combination and content of PVA fibres in order to enhance the flexural strength of HDM. Its specific objectives are:

- (1) To investigate if the combination of different sizes of PVA fibres may enhance the flexural strength.
- (2) To determine the appropriate size of PVA fibre for the enhancement of flexural strength.

The author believes both above investigative works may create the logistic base for the development of HDM.

2 Necessity of this research work

As we know that the concrete and mortar are brittle materials due to very weak transitional zone in between the phases of the matrix. All experimental results have shown that all failures in ordinary concrete or mortar are initiated from the transition zone, and due to this reason, the structural elements are failing before providing any ductility. However, in modern construction industries we have badly needed ductile structural elements which may not only be capable to bear the high compressive stress but also the tensile and flexural stress.

3 Experimental procedure

In all series of these investigative works, three types of PVA fibres were used. Their details are given in Table 1.

3.1 Combination of different types of PVA fibres

For this investigative experimental work, main two types of PVA fibres, REC15 and RECS100 were chosen. In this attempt, quite thick and long fibres were chosen, assuming that they could be well dispersed and properly coated while mixing in big mixers at batching plant.

In order to study their effect (with a single or in combination) on flexural behaviour of HDM, different matrix of mix proportions was prepared for the experiment. Mix design and all testing procedures were carried out with the specifications given by Japan Industrial Standard (JIS). In some cases, fly ash was also added to increase the matrix of paste in the mix with consideration that the fibres might be coated well with the sufficient available paste in the mix. The content of fly ash was used 35% of total powder in case (a) and 30% in case (b). Detail of mix proportions, with variable combination of two different fibres, is shown in Table 2.

In order to enhance the workability and viscosity of base mortar, 1.5% of super plasticizer (by weight of powder material) and 0.3% of viscosity agent (by weight of water) were used in mix 1. And, 1.0% of super plasticizer and 0.4% of viscosity were used in the mix 2.

3.2 Challenges on thinner and shorter PVA fibres

The second investigative point was to determine the appropriate size and content of PVA fibre. For this purpose, thinner and shorter RMH182 ($\phi 14 \mu\text{m} \times 6 \text{ mm}$)-type PVA fibre was used.

It is because, as it is known from Table 1, the both tensile strengths and Young's modulus are higher than those of the other two types. Assumptions were made that it may give better results if these fibres are made uniformly

Table 1 Properties of PVA fibre used in experimental investigation

Parameters	Characteristics		
	RMH182	REC15	RECS100
Fibre type			
Diameter (mm)	0.014	0.04	0.1
Length (mm)	6	12	12
Specific gravity	1.3	1.3	1.3
Tensile strength (MPa)	1900	1600	1200
Young's modulus (GPa)	43	41	28
Fibre elongation (%)	5	6	6

Table 2 Mix proportion table for two different types of PVA fibres

Mix no.	Fibre content (%)		Unit content (kg/m ³)			
	REC15	RECS 100	W	C	F	S
1-(a)	2.0	0	300	857	0	1087
1-(b)	2.0	0	300	600	257	992
1-(c)	0.5	2.0	300	857	0	1073
1-(d)	1.0	1.5	300	857	0	1073
2-(a)	2.0	0	345	700	300	734
2-(b)	1.0	1.0				
2-(c)	0.5	1.5				
2-(d)	0	2.0				

W Water, C Cement, S Sand, F Fly ash

distributed and firmly coated with mortar. Mix proportions for these series of experimental investigation are shown in Table 3.

3.3 Mixing procedure

Mortar mixer was used for the mixing of fibre mortar. Six litres were mixed per one batch. Since powder of viscosity agent was used, it was premixed with cement in the bucket by small scoop. HDM mixing method [25] was used for all steps of mixing procedure.

4 Workability evaluation and strength tests method

The first investigative evaluation of the prepared mortar was just the visual check with an eye and touched by hand. The second was flow table test followed by mechanical properties tests. Visual check was almost similar in all series of mixed fibre mortar. No any fibre lump was noticed throughout the mixed mortar. Each fibre was found uniformly distributed and well coated with mortar/paste. Moreover, it was found with the tentative check of the viscosity by hand and high ductility was found to be easier for placing, compaction and finishing. In the first phase of

the experiment, all table flow values of fibre mortar were obtained greater than 150 mm. The flow value of thicker fibre mortar was found more than that of thinner values.

In order to carry out the analytical judgment, table flow values of the second-phase experiments will be discussed later in result and analysis section.

After visual check and the workability test, three small beams with sizes of 400 mm × 100 mm × 50 mm (length × width × depth) were produced in all series of experiments for 7-day bending tests. Since the comparative result was required from these series of tests, it was not waited for 28 days.

Bending test was carried out with four-point loading method, as shown in Fig. 1. Strain gauge was set at the exact centre of the depth to measure the deflection (strain) while increasing load (stress) momentarily.

5 Test results and analysis

Flexural strength test results were obtained from both phases of experimental investigation. First-phase result was from the blending of the two types of thicker PVA fibre mortar, and the second one was to challenge on the thinnest and shortest PVA fibre mortar; and then make

Table 3 Mix proportion for ranging percentage of RHS182 and 2% of REC40 and RECS100 type fibres

Mix proportion condition					Unit content (kg/m ³)					
W/C (%)	SP (% by C)	VA (% by W)	Fibre type	Fibre content (% by vol)	W	C	S	Fibre	SP	VA
30	1.5	0.3	RHS182	1.0	375	1250	565	13	18.75	1.125
				1.5			559	19.5		
				2.0			552	26		
			REC40	2.0						
			RECS 100	1.0						

W Water, C Cement, S Sand, SP Super Plasticizer, VA Viscosity agent

Fig. 1 Bending test method

comparison study with the other two types, used in the first phase.

5.1 Results on combination of different types of PVA fibres

The result of 7-day flexural strength for the first phase of experiments (combination of two types of fibres) is summarized in Table 4.

When analysing the average flexural strengths and their respective variation coefficients of each mix proportion, the following concepts can be made for further enhancement.

- (1) Flexural strength of mix no. 1-(b) (7.4 MPa) was achieved larger than that of mix no. 1-(a) (6.3 MPa). This result supported the clause that the inclusion of mineral admixtures (i.e. fly ash, grounded blast furnace slag, silica fume, metakaolin, etc.), as partial replacement of cement, may enhance the flexural strength of HDM. In this experiment, fly ash was used as mineral admixture.
- (2) Total fibre content is more (2.5%) in the mix 1-(c) and 1-(d); however, the flexural strengths of both were obtained as 8.1 MPa and 7.8 MPa, respectively. Values

were lower than expected ones, even lower than of other mixes with fibre content of 2.0% only (except in the mix 1-(a) without addition of fly ash). This result shows that the increasing the fibre content is not the solution to enhance the flexural behaviour of HDM, but should be concentrated on enriching the basic mortar (in terms of total paste amount and its viscosity). It supports the idea as comparing whole data between mix 1 and mix 2 because mix 2 has more viscous paste than that of mix 1.

- (3) The variation coefficient of mix 2-(b) was found unexpectedly high. It is the matter for the further investigation. Content of thicker fibre is higher than thinner in other mixes, but it is the same in this mix. Before mixing, both types of fibres were roughly blended by hand in the bucket and charged into the mortar mixer. Here, theoretical consideration is made that is the whole capacity of thicker fibre could not be sufficient to disperse thinner fibre in micro-level inside the mortar while mixing. However, this hypothetical clue would have been clarified (right/wrong?) if one more parameter, higher amount of thinner fibre with lower amount of thicker one, would have been added in these series of experimental investigation.
- (4) In an overall analysis of achievement data from these phases of experimental results, blending of two different fibres may not meet the target of developing HDM for required level flexural strength. Thus, concentration should still be made on a single size PVA fibre.

5.2 Results on thinner and shorter PVA fibres

Experiment result was obtained as according to the author's assumption that if thin and short fibres are uniformly distributed and firmly coated inside the base mortar, it may enhance the flexural behaviour of HDM. Deflection of RMH182 fibre HDM beams was the largest, followed by REC15 and then RECS100 types HDM beams.

Table 4 Seven-day flexural strength of the first-phase fibre mortar experiments

Mix no.	Fibre content (%)		Average flexural strength (MPa)	Variation coefficient (%)
	φ40 μm × 12 mm	φ100 μm × 12 mm		
1-(a)	2.0	0	6.3	6.9
1-(b)	2.0	0	7.4	5.8
1-(c)	0.5	2.0	8.1	4.6
1-(d)	1.0	1.5	7.8	2.4
2-(a)	2.0	0	9.5	7.0
2-(b)	1.0	1.0	9.2	18.1
2-(c)	0.5	1.5	8.4	1.9
2-(d)	0	2.0	8.5	6.0

Micro-cracks developed in the first ones were thinner and number of times than those developed in later two types.

Result of table flow values and seven-day flexural strengths with respective variation coefficients of fibre mortar in the second phase of experimental series (RMH182 ($\phi 14 \mu\text{m} \times 6 \text{ mm}$), with varying content of 1.0, 1.5 and 2.0%, and 2% content of both REC15 ($\phi 40 \mu\text{m} \times 12 \text{ mm}$) and RECS100 ($\phi 100 \mu\text{m} \times 12 \text{ mm}$) is in Table 5.

Table flow values of each type of fibre are shown in Fig. 2.

When analysing all data listed in Fig. 2, the following discursive points can be made.

- (1) Table flow values of RHS182-type fibre mortar linearly decreased while increasing the percentage of fibre. The value obtained 172 mm in 1% fibre content was decreased to 152 mm in 1.5% and then further to 138 mm in 2.0%. It seems the workability of fibre mortar is inversely proportion to the percentage of fibre content. This result backs up the theoretical aspects for the required amount of mortar for coating of fibres as well as the remaining free mortar required for the deformation. When fibre content is increased in mortar with any proportion, numbers of fibres also increase in the same proportion. The total outer surface area of fibres also increases in the same proportion demanding the amount of mortar with same proportion required for coating. It means the total amount of free mortar decreases in the same proportion, required for the deformation, resulting in a linear decrease in workability with increase in fibre

Fig. 2 Table flow values of fibre mortar in second phase of experiments

content. The study of this phenomenon may help to design the theoretical mix design of fibre mortar for the required amount of workability, i.e. table flow value.

- (2) In another result, the flow value of RECS100 fibre mortar is maximum (252 mm), followed by that of REC40 mortar (162 mm) and then of RHS (138 mm). The overall argument for this trend of result is similar to that of above; however, the analytical procedure may differ a little due to variation on length and diameter of fibres used which may differ with the aspect ratio.

The flexural strength test result of second-phase experiments is shown in Fig. 3.

Table 5 Table flow values and 7-day flexural strengths of fibre mortar in second phase of experiments

Fibre type	Fibre content (%)	Table flow (mm)	Flexural strength (MPa)	Average (MPa)	Variation coefficient (%)
$\phi 14 \mu\text{m} \times 6 \text{ mm}$	1.0	172	7.72	7.98	6.9
			7.60		
			8.60		
	1.5	152	9.01	9.01	4.1
			9.38		
			8.65		
	2.0	138	9.07	9.09	1.4
			9.23		
			8.97		
$\phi 40 \mu\text{m} \times 12 \text{ mm}$	2.0	162	8.97	8.65	5.9
			8.91		
			8.06		
$\phi 100 \mu\text{m} \times 12 \text{ mm}$	2.0	252	7.66	8.01	3.7
			8.21		
			8.15

Fig. 3 Flexural strength result of the second-phase experiments

From the study of data in figure, some points can be drawn as:

- (1) While increasing the content of RHS182 fibre from 1.0 to 1.5%, the flexural strength was significantly increased from 7.98 to 9.01 MPa, with a difference of 1.03 MPa. However, when further increasing fibre content to 2.0%, the increment was very small (9.09 MPa), with the only difference of 0.08 MPa. The reason behind it should be either each fibre could not be distributed uniformly throughout the mortar (development of unseen micro-lumps) or could not be well coated.
- (2) Flexural strength of 1.5% of RHS182 fibre mortar (9.01 MPa) was found more than those from 2% of REC40 fibre mortar (8.65 MPa) and RECS100 fibre mortar (8.01 MPa). Author assumes that there are more numbers of fibres in RHS182 than in others two, with which inter-fibre distance within mortar is less than that in case of two other fibres. This assumption can also be backed by the visual check of cracks in bending test. There were numerous thin cracks developed in case of RHS182 fibre mortar, but less numbers of thick cracks in other two types of fibre mortar.
- (3) There should be optimum content of fibre depending upon the type of fibres, workability and viscosity of base mortar, which may provide the optimum value of the flexural strength.
- (4) Since specific gravity and cost of PVA fibres are same, the use of thinner and shorter fibres is economical in HDM.

In overall observation and experimental data analysis, thinner and shorter PVA fibres need more mortar than thicker and longer ones to be well coated. If the requirement of dispersion and coating is met, thinner and shorter fibres give more flexural strength than that from thicker and longer

ones. Experimental data showed that the combination of two different fibres does not enhance the flexural strength. So, a single size fibre is better to be used with consideration of other parameters in order to enhance the flexural behaviour of HDM.

6 Conclusion

The following conclusive points were drawn from this experimental investigative work.

- Thinner and shorter PVA fibres need more amount of mortar to be well coated.
- If the requirement of dispersion and coating can be fulfilled, thinner and shorter PVA fibres are better to use.
- Only one type of PVA fibre is better to use than the combination of two different types.
- The use of mineral admixtures increases the both workability and flexural strength of HDM.

7 Future scope

The author has focused on developing High-Ductile Mortar (HDM) with a target of the flexural strength more than 12 MPa, required for tunnel precast segments, replacing steel fibres with short and thin synthetic fibres in order to overcome the problems on mixing as well as to enhance the flexural strength and ductility behaviour. Since, it is very preliminary investigative work, the focus was given on different parameters to identify qualitatively rather than quantitatively.

The result obtained in this paper will be followed by the investigative work on alteration of mix proportion as well as casting method.

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Compliance with ethical standards

Conflict of interest The corresponding author states that there is no any conflict of interest.

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