Investigation on Dispersion and Mixing Method of PVA Fibers with Cement Paste

Tek Raj Gyawali

School of Engineering, Faculty of Science and Technology, Pokhara University
Pokhara Lekhnath-30, Kaski, Nepal
Tekrg[at]pu.edu.np

Abstract: ***Flexural strength of fiber paste/mortar greatly depends upon the dispersion and coating condition of fibers. Attempts were made for the dispersing of thin and short Poly-Vinyl Alcohol (PVA) fibers [1] and mixing method of fiber paste. It was found that the dispersing effect of fibers were better in air pressure. The fiber paste mixed in chopper mixer revealed 27% increase in flexural strength than that mixed in conventional mortar mixer. Pre-dispersed fibers, with air pressure, used in chopper mixer resulted in 34% increase. Compressive strengths of later two cases were slightly increased in same range than that in mortar mixer.***

Keywords: Poly-Vinyl Alcohol (PVA) fibers, Dispersion, Mixing, Fiber paste, Flexural Strength

1. Introduction

Concrete is very brittle material which is strong in compression but very weak in tension. In order to overcome these problems of less tensile and ductility, steel reinforcement bars are used in reinforced concrete structures. Other deficiencies of concrete are creep, shrinkage and cracking problems.

With modernization on concrete design and construction work, many attempts have been made and implemented to enhance the compressive strength of concrete like in Self Compacting Concrete (SCC), High Strength Concrete (HSC) and High Performance Concrete (HPC).

With advancement on the requirement of structural performance like in flexural strength and ductility requirement, different types of fibers have been developed to be mixed with cement paste, mortar or concrete.

2. Literature Review

Depth literature review was carried out in order to select the appropriate parameters for investigative work.

2.1 Development History of Steel Fiber Reinforced Concrete (SFRC)

Fiber reinforced cements and concrete (FRC) are firmly established as construction materials. Since the early 1960's extensive research and developments have been carried out with FRC materials leading to a wide range of practical applications [2]. Inter-relation of the structural performance of FRC with material constituents, processing and mechanical properties is shown in **Fig. 1** [Victor C. Li, Michigan University]. As shown in figure, it can be checked that 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 the structural application of FRC through its mechanical properties.

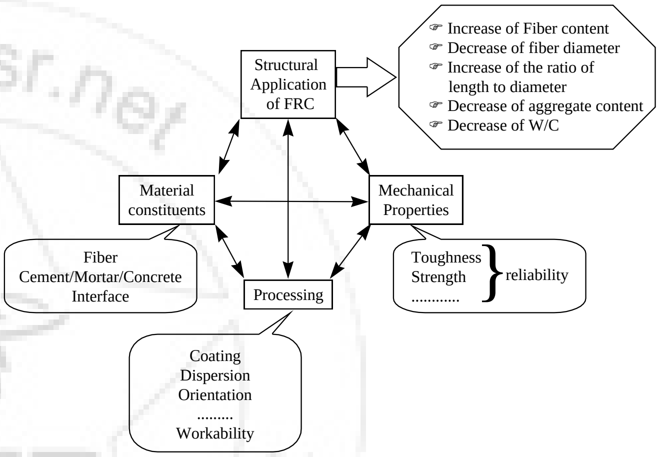

Figure 1: Chart for the evaluation of the structural application of FRC [Victor C. Li, Michigan University]

With regard to the production of FRC, many trials had been carried out, especially with the timing of adding fiber materials when mixing and other materials as well. American Concrete Institute had listed the following 5 methods of adding fiber materials in 1982 [3].

1. Feed the fibers with the aggregate and cement on the central conveyor belt.
2. Blend fibers and aggregate before charging into the mixer and then use standard mixing procedure.
3. Blend fine and coarse aggregate. Add fibers to the mixer operating at mixing speed then add water and cement.
4. Add fibers to previously charged aggregate as the water. Finally add cement and remaining water.
5. Add fibers as the last step to mixed concrete.

However, American Concrete Institute, ACI 6.44-3R (1993), has indicated that fibers should be added to a fluid mix, either as the last stage of mixing or added to the mixer with the aggregates [4]. Both documents of ACI indicated that care should be taken to avoid fiber balling. Many recommendations were made such as to avoid the clumps of fiber adding and slow rate of adding to allow dispersion.

Bartos and Hoy [5], [6], [7] had studied about the effect of mixing procedure on the properties of fiber reinforced concrete and especially with the feeding sequence of ingredients into the mixer. Its methods and descriptions are shown in **Table 1**.

Table 1: Method and descriptions of SFRC mixing methods

Method no.	Description
1	Coarse aggregates, cement, pfa and fines are layered in the mixer. The mixer is started and the water and super plasticizer are added. After two minutes mixing fibers are added and mixing continues for 30 seconds.
2	Mix coarse and fine aggregates, cement and half water for 1 minute, add remaining water and mix for a further minute. Add fibers and mix for 30 seconds.
3	Mix fines, cement and half water for one minute, add remaining water and mix for one minute. Add fibers and coarse aggregate and mix for a further 30 seconds.
4	Mix fine aggregate, fibers, cement and half water for one minute, add remaining water and mix for one minute. Add coarse aggregate and mix for a further 30 seconds.
5	Mix the cement, water and super plasticizer for 90 seconds, and then add aggregates and fibers. Mix for a further minute.

The method of adding water and the time of adding fibers 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 fibers becoming logged 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 [6], [7].

Japan Concrete Institute [8] has recommended the mixing of concrete should be followed by feeding of fiber materials. The mixing volume of one batch should be less than 80% of the total volume capacity of the mixer. Mixing time is dependent upon the volume, type of mixer and concrete type as well. In general, more than 3 minutes is recommended for tilting type mixer and more than 2 minutes for forced action mixer. Feeding of fibers should be carried consequently by running mixers and it should be done in such a way that all fibers should be dispersed uniformly. Feeding time for fibers depend upon the mixing volume and content of fibers. Generally, it should be 1~2 minutes. After all feeding of fibers, further mixing should be carried out for about one minute. The use of dispenser and vibrated chute or sieve is also recommended for feeding fiber materials.

2.2 Existing Problems with SFRC

In normal practice, the mixing of steel fiber reinforced concrete (SFRC) is carried out with the first method, described in **Table 1**, which is also recommended in most of the standards worldwide, i.e. ACI, JCI etc. However, it is noticed still difficult to make the even distribution of fiber materials in mixed concrete with this method in almost all types of existing mixers ever developed. Moreover, fibers may clump or form balls if more than 2% (by volume) of steel fibers are mixed in concrete. It is needless to say that the increase in the content of fiber means the increase in the requirement of external energy to make the fibers well distributed throughout the concrete. It means electric consumption of the mixer is more for the concrete with higher amount of fibers. In the forced type double axis mixer of 1.5m^3 capacity [9], when mixing steel fiber reinforced concrete (SFRC) of slump about 10 cm, load becomes double than that for ordinary concrete. This becomes 4 times in the case of slump 5cm. From this result, it can be understood that the load becomes extremely large when mixing the dry consistency SFRC with its slump of 2~3 cm. In order to avoid the balling of the fibers within short time of introducing, dispensers are being used. These dispensers help the fibers to be introduced into concrete in the dispersed form, which minimize the chance for balling. However when using one dispenser with its capacity of 40kg/min, it takes about 4 minute to introduce all fibers into the mixer for mixing SFRC with 2% fibers. It means it requires more than 5 minutes mixing SFRC with 2% SF in 1.5m^3 mixer. Therefore, the main reason to limit the fiber content from 0.5% to 2% in the existing mixer should be due to the electric load and the mixing time.

2.3 Development of Thin, Short and Light Fibers

Synthetic fibers 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 fibers are further optimized; greater improvements can be gained without increasing the reinforcement costs [10]. Moreover, unlike the steel fiber which is highly corrosive in nature, there is no corrosion concern regarding synthetic fibers in concrete.

During the past 20 years (since early 1990s), Poly-Vinyl Alcohol (PVA) fiber has been introduced in the production of cementitious composites [10], [11]. Kuraray was first Japanese company to develop such PVA fibers and commercialize worldwide. PVA fibers have high tenacity, high modulus, low elongation, light weight, good resistance against chemicals (alkaline), good adhesion to cement matrix. PVA fibers have tensile strength ranging from 880 to 1600 MPa, elongation of 6%, tensile modulus ranging from 25 to 41 GPa and specific gravity of 1.2 [1].

PVA fibers 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 behavior, is called engineered cementitious composites (ECC) [10], [11].

With development of such PVA fibers, many researches have been carried out to study the mechanical behavior of hardened PVA fibers reinforced mortar depending upon types and percentage of PVA fibers. However, any research works have not been noticed to investigate the dispersing method of such thin and short fibers one by one inside the mortar and coating firmly by mortar. This paper has attempted many trials to investigate the appropriate method of dispersing and mixing of PVA reinforced cement paste to set the base for the development of High Ductile Mortar (HDM) with significant high flexural strength and high ductility.

3. Objective

This paper aims to investigate the appropriate method for dispersing and mixing of thin and short PVA fibers inside cement paste in order to enhance the flexural strength of PVA fiber cement paste. Its specific objectives are:

(1) To carryout different trials of dispersing methods and select the appropriate method of dispersion for further trials of different mixing methods.
(2) To carryout different trials of mixing methods and select the appropriate method of mixing to analyze the mechanical behaviour of PVA fiber paste.

4. Experimental Procedure and Preliminary Judgement

In this experimental investigation work, basic mix proportion of cement paste was kept constant with water cement ratio as 0.4. RMS702 type PVA fiber, shown in **Fig. 2**, of its diameter of 26 micron and 6mm length (thinnest and shortest) was used. It is resin bounded type fiber. Its tensile strength is 1.6 GPa and modulus of elasticity as 39 GPa [1]. PVA fiber content was used 2.0% by volume in all mixes. Investigative parameters were chosen as dispersing and mixing methods.

Fig. 2: Type of PVA fiber used in experiment (RMS702)

4.1 Trials on Dispersion Method

Theoretical concept was made that if PVA fibers can be introduced inside to paste with uniform distribution single by single and coated by paste firmly, it would have given higher degree of flexural strength. Practical attempts were made with commercially available apparatus and one developed prototype chopper mixer for the investigation. Using these different dispersion methods, initial visual check was based only upon expertise's naked eye if all these thin and short PVA fibers, which were generally in accumulated in bulk volume, might be separated in single form or not.

4.1.1 Dispersion of PVA Fibers with Air Pressure

In this method, PVA fibers were placed inside container and then air pressure was supplied to disperse the fibers, as shown **Fig. 3 (a)**. Since bulk volume of PVA fiber was large, charging to the container was done part by part which took relatively long time for charging. Dispersed condition of PVA fibers is shown in **Fig. 3 (b).**

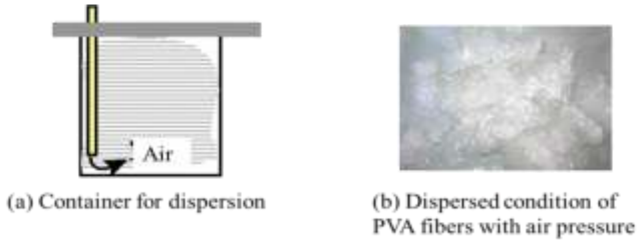

Fig. 3: Container used for dispersion of PVA fibers with air pressure and condition of dispersed fibers

Initial result was found very satisfactory with the distribution condition in related with separation of attached fibers with each other apart. However, with visual check judgment, that practicable simulation was vitally important to balance the amount of pressure to disperse the induced volume of PVA fibers. These dispersed fibers were used for mixing fiber paste.

4.1.2 Dispersion of Fibers in ESG Mixer

ESG mixer, developed by author [12], was also used for this investigation. PVA fibers were charged to ESG mixer, with 4 units of 100 mm opening size, through Φ100×500 mm hose pipe and dispersed fibers were collected in container in the exit for the investigation of dispersion condition. Set-up for dispersing experiment of PVA fibers in this mixer is show in **Fig. 4**.

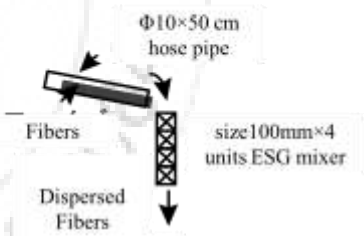

Fig. 4: Set-up for Dispersing experiment of PVA fibers in ESG mixer

Although the dispersion of fibers was observed to some extent, bulk attachment of fibers was clearly seen. Moreover, fibers were found accumulated on the slope surface of ESG mixer units. Although, use of vibrator was sought to enhance the dispersion efficiency it was made pending for further investigation.

4.1.3 Pre-mixed Method in ESG Mixer

Similar size and numbers of ESG mixer units were used in this experiment. Batched cement was first layered in conveyor belt. PVA fibers were set to be sent through hose pipe at the exact rate as per the mix design. Then, conveyor belt and hose pipe were started at the same time to charge the mix of cement and PVA fibers into the ESG mixer. Pre-mix of cement and PVA fibers was collected in container for the further investigation. Experimental set-up is shown in **Fig. 5**.

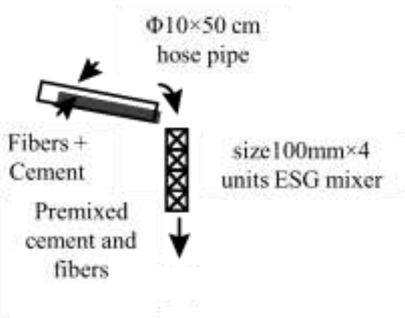

Fig. 5: Set-up for Dispersing of fibers with dry cement in ESG mixer

Due to accumulation of cement powders and fibers in slope surface inside ESG mixer, this result was made pending for further investigation. However, the prediction was made that the use of vibrator might have given the better result.

4.1.4 Dispersion of PVA Fibers in Juice Mixer

Commercially available juice mixer was used to investigate if PVA fibers can be separated from each other with centrifugal force developed due to revolving speed of bottom knives. Batched fibers were charged and juice mixer was started for few seconds to judge the dispersing condition of PVA fibers. Dispersion condition of PVA fibers is shown in **Fig. 6.**

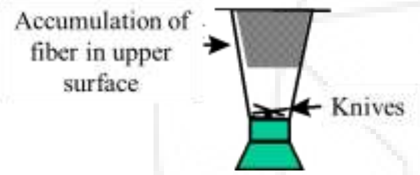

Fig. 6: Set-up for Dispersing of fibers with dry cement in ESG mixer

Due to centrifugal force developed by speedily revolving knives at bottom, all fibers were accumulated at upper part of juice mixer without any dispersion. It was rejected for further investigation.

4.1.5 Dispersion of PVA fibers in prototype developed chopper mixer

One prototype chopper mixer was developed for this trial experiment. Its detail is shown in Fig. As similar procedure to the juice mixer, batched fibers were charged into chopper mixer and the dispersion was made with starting chopper mixer for few seconds. Developed prototype chopper mixer and condition of dispersed PVA fibers is shown in **Fig. 7**.

Just after starting of chopper mixer, bulk of PVA fibers was revolved with speed of knives and immediately accumulated around the inner surface of chopper mixer. This method for pre-dispersion of PVA fibers was also rejected for the further investigation.

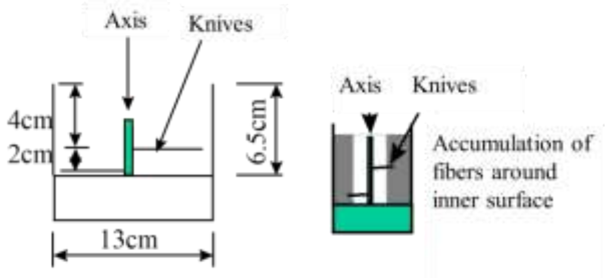

Fig. 7: Developed prototype chopper mixer and dispersion condition of PVA fibers in it

From above trial tests, only the pre-dispersed PVA fibers was considered as the parameter for mixing the PVA fibers reinforced cement paste.

4.2 Trials on Mixing Methods

Mixing experiment parameters were chosen as (1) Mixing in conventional mortar mixer, (2) Mixing in juice mixer, (3) Mixing in chopper mixer, and (4) Mixing in chopper mixer with use of pre-dispersed PVA fibers with air pressure.

Similar mixing method was adopted in all trials. Cement paste was first mixed for one minute. Then PVA fibers were charged part by part. After finishing the charging of fibers, then it was mixed for further one minute.

4.2.1 Mixing in Mortar Mixer

Visual condition PVA fiber paste, mixed in mortar mixer, is shown in **Fig. 8**. In this mixing method, small flocks of fibers were found throughout the mix. It was due to the centrifugal force developed by the revolving wing of the mixer. Only water, but not the paste, was observed inside each flock of fibers. Fiber paste mixed in this mortar mixer (conventional mixing method) was considered as the base for the comparison with other methods.

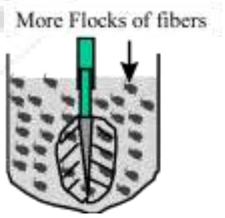

Fig. 8: Condition of PVA fiber paste mixed in mortar mixer

Six numbers of specimens of Φ50mm×10mm were produced for compressive strength test and three numbers of 40mm×40mm×160mm specimens for bending test.

3.2.2 Mixing in juice mixer

Mixing of fiber paste was conducted in juice mixer with the similar method that adopted in the juice mixer. There was no problem for mixing the cement paste for initial one minute. However, difficulty was noticed while charging the fibers in the paste. Charging the fibers during the mixing was impossible since all light fibers blew up due to the centrifugal force developed by revolving knives. Charging was done part by part and covering was done; then mixing was carried out.

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This process was continued until the finishing of the whole batched fibers. Then fiber paste was mixed for further minute. In this mixer, it was the most difficult to induce the fibers inside the paste and make them uniformly distributed. Due to centrifugal effect of bottom knives, all fibers got accumulated in upper surface. This method was rejected and no any specimens were produced for the tests. Condition of PVA fiber paste, mixed in juice mixer, is shown in **Fig. 9**.

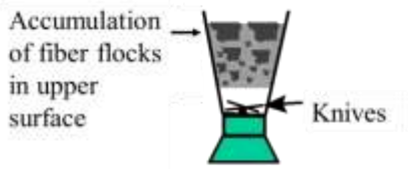

Fig. 9: Condition of PVA fiber paste mixed in juice mixer

3.2.3 Mixing in Chopper Mixer

The method of mixing paste and charging fibers adopted in chopper mixer was similar to that in mortar mixer. Condition of PVA fiber paste, mixed in chopper mixer, is shown in **Fig. 10**.

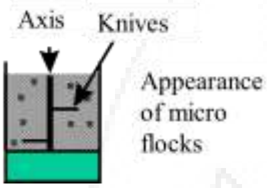

Fig. 10: Condition of PVA fiber paste mixed in chopper mixer

Mixing condition of fiber paste was observed better than that in mortar mixer. However, some micro flocks of fibers were noticed inside the fiber paste. Specimens, similar to those from the fiber paste mixed in mortar mixer, were prepared for strength tests.

4.2.4 Mixing in Chopper Mixer with Pre-dispersed Fibers

In this method, PVA fibers were pre-dispersed with air pressure and the mixing of fiber paste was conducted with similar to above method.

Mixing performance was noticed better than above three methods. Appearance of micro flocks was also less than that of fiber paste mixed in chopper mixer using non-dispersed Specimens were prepared for the strength tests.

5. Results and Discussions

In this inventive research work, the main focus was to increase the flexural strength of PVA induced fiber paste by means of uniform distribution and well coating of each fiber with paste. Two major parameters were chosen as dispersion method and mixing method. Dispersion method was analyzed visually. PVA fibers dispersed with air pressure were found the most effective and it was chosen as parameter for the mixing method. Other dispersion methods were rejected. Conventional mixing method (mixing in mortar mixer) was considered the base for comparison. Juice mixer and developed prototype chopper mixer were used for mixing fiber paste in order to compare with conventional mixing method. However, the fiber paste mixed in juice mixer was rejected for the strength test from the visual check analysis. Therefore, fiber pastes mixed in chopper mixer, with and without pre-dispersed fibers, were taken as two major parameters to compare the flexural and compressive strengths with those of conventional mixing method. **Table 2** shows the result of 7 days flexural strength test.

Table 2: Seven days flexural strength of fiber paste mixed with different methods

Mixing Method	Wt, (gm)	Ds (gm/cm^3)	Avg, (gm/cm^3)	VC (%)	FL (kN)	FS (MPa)	Avg. (MPa)	VC (%)	Increment (%)
Mortar Mixer	471	1.84	1.84	0.1	39.5	9.3	9.3	5.1	100
	472	1.84			37.5	8.8			
	472	1.84			41.5	9.7			
Chopper	467	1.82	1.82	0.0	45.5	10.7	11.8	8.3	127
	467	1.82			53.5	12.5			
	467	1.82			51.5	12.1			
Chopper*	471	1.84	1.84	0.3	54.5	12.8	12.4	4.1	134
	470	1.84			54.0	12.7			
	473	1.85			50.5	11.8			

*Fibers were pre-dispersed by air pressure, Wt: Weight of specimens, Ds: Density of specimens, Avg.: Average, FL: Flexural Load, FS: Flexural strength, VC: Variation coefficient.

Average 7 days flexural strength of PVA fiber paste mixed with conventional method in mortar mixer was obtained 9.3 MPa. This result clearly shows that the inclusion of PVA fibers in cement paste increases the flexural strength. The PVA fiber paste mixed in chopper mixer gave the flexural strength of 11.8 MPa, which was 27% more than that of conventional mixing method. This result developed the conceptual idea that the knives used in chopper mixer have more efficiency to disperse thin and short fibers within paste than that of the wing of mortar mixer. Interestingly, PVA fiber paste mixed in chopper with use of pre-dispersed fibers with air-pressure further increased the flexural strength to 12.4 MPa, which was 34% more than that of conventional mixing method. This preliminary inventive research work revealed the conclusion that the dispersion condition of PVA fibers is the main parameter to enhance the flexural strength of fiber paste.

Table 3 shows the 7 days compressive strength results of respective fiber pastes. 7 days average compressive strength of the PVA fiber paste that mixed with conventional mixing method was obtained 29.34 MPa. The paste mixed in chopper mixer gave 31.79 MPa, which was only 8% more than that of conventional mixing method. Furthermore, pre-dispersed PVA fibers with air-pressure used for mixing in chopper gave 32,65 MPa, which was 11% more than that of conventional mixing method.

Analyzing both results of flexural and compressive strengths of PVA fiber paste, conclusion can be made that inclusion of PVA fibers in paste enhances the flexural strength which is greatly depended upon its dispersion condition inside paste.

Table 3: Seven days compressive strength of fiber paste mixed with different methods

Mixing Method	CL(kN)	CS (MPa)	Avg, (MPa)	VC (%)	Increment ‘ (%)
Mortar Mixer	453	28.31	29.34	6.0	100
	511	31.94			
	435	27.19			
	452	28.25			
	477	29.81			
	489	30.56			
Chopper	485	30.31	31.79	7.0	108
	536	33.50			
	469	29.31			
	490	30.63			
	507	31.69			
	565	35.31			
Chopper *	502	31.38	32.65	4.4	111
	525	32.81			
	489	30.56			
	530	33.13			
	538	33.63			
	550	34.38			

*Fibers pre-dispersed by air pressure, CL: Compressive Load, CS: Compressive Strength, Avg.: Average, VC: Variation coefficient.

6. Conclusions

This preliminary investigative research work was carried out with the target of developing high ductile mortar. The use of developed prototype chopper mixer for mixing PVA paste increased flexural strength and compressive strength by 27% and 8% respectively. Use of pre-dispersed PVA fibers for mixing in chopper mixer gave further increment by 34% and 11% respectively. The most important conclusion drawn from this research was that the dispersing and coating conditions of each PVA fiber is vitally important to enhance the flexural behavior of PVA fiber paste.

7. Future Scope

Author has focused on developing High Ductile Mortar (HDM) with target of the flexural strength more than 12 MPa, required for tunnel pre-cast segments, replacing steel fibers with short and thin synthetic fibers in order to overcome the problems on mixing as well as to enhance the flexural strength and ductility behavior. 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, modified mixing process as well as casting method.

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Author Profile

Tek Raj Gyawali achieved his BS in Structural Engineering from Tongji University, Shanghai, China, in 1989. He achieved his MS and PhD degrees in civil engineering from the University of Tokyo, Tokyo, Japan in 1993 and 1999 respectively. He has done lot of research and developments works in developing new engineering materials/products. He also carried out joint-research works in Three Gorges Project, China, as concrete expert, for 2 years and in University of Paisley, UK, for one year. His research interest is basically to develop new engineering materials and technologies as well as to enhance the quality control in construction. Now, he is Professor at Pokhara University, Nepal.