ANNEX C

Study of the Distribution and Orientation of Fibers in Cast Cylinders

STUDY OF THE DISTRIBUTION AND ORIENTATION OF FIBERS IN CAST CYLINDERS

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C.1. Introduction

The compacting procedure used in the fabrication of fiber reinforced concrete specimens and elements is normally expected to influence the distribution and orientation of the fibers. This phenomenon has been studied by several researchers, such as Edgington and Hannant (1972), Stroeven (1977, 1979), Soroushian and Lee (1990), Toutanji and Bayasi (1998), and Saldivar (1999). Most of these works conclude that the vibration of the element during compaction produces some segregation of the fibers (i.e., more fibers at the bottom) and a preferential orientation of the fibers along horizontal planes (i.e., more horizontal fibers than vertical ones). The resulting heterogeneity and anisotropy leads to non-uniform mechanical properties.

The present work focuses on the distribution and orientation of fibers in standard 150×300 mm cylinders with two principal objectives. The first objective is the presentation of a simple methodology to evaluate the distribution and orientation of fibers within the cylinder (used for compression and tension tests). The approach consists of cutting the specimen longitudinally along a diameter and then transversely at several heights. The fibers that appear on the cut surface are counted, and average fiber densities are determined for different areas of the cuts for the purpose of comparisons. The second objective is to apply this methodology to study the uniformity of the fibers in specimens that are vibrated externally and tamped manually.

C.2. Materials Used, Fabrication and Cutting Procedure

Materials studied

A single batch of concrete consisting of CEM I 52.5R cement, 0-5 mm sand and 5-12 mm gravel was used for the manufacture of the test specimens. The fine aggregate consisted of crushed limestone with a coefficient of absorption of 1.61% and the coarse aggregate was crushed gravel with a coefficient of absorption of 0.84%. The water-cement ratio was 0.57. The fibers used were Bekaert Dramix 80/60BN, cold drawn, low carbon, hooked-ended steel wire fibers. They were 60 mm long, with a diameter of 0.75 mm. A superplasticiser (DARACEM 205, naphthalene-based, density 1.16 kg/lit., 35% solids content) was incorporated in the concrete. The mix contained 40 kg/m^3 of the fibers, corresponding approximately to a volume fraction of 0.5%. The mix proportions can be found in Table C.1.

Table C.1. Mix Proportions

Cement Kg/m^3	Fine aggregate Kg/m^3	Coarse aggregate Kg/m^3	Water Kg/m^3	Superplasticizer liters
349	873	978	215	2.1

Fabrication of the Specimens

The following mixing procedure was used: firstly, the coarse aggregate and the fine aggregate were incorporated into the mixer, followed by the cement and 90% of the mix water; the superplasticiser was added to the remaining 10% of water and this solution then added to the mix; the components were mixed for a period of 2 minutes; and after this, the fibers were added one handful at a time and the mixing allowed to continue for a further 3 minutes.

The slump test was performed after mixing to ensure that the mix was of suitable workability; the fresh concrete had a slump of 8.5 cm. Immediately afterwards 9 standard cylindrical specimens (150 mm diameter, 300 mm length) were cast. Three were compacted manually by hand tamping with a metal rod, adhering to the standard procedure of filling a third of the mold, tamping 25 times with the bar and then repeating the process for the remaining two thirds of the mold. Three other specimens were compacted using a vibrating table of 50 cycles/sec. For each, the mold was half filled and vibrated for 10 seconds, and then fully filled and vibrated for a further 15 seconds.

In addition, three molds incorporating rings of 10 mm width and 1 mm thickness, at mid-height, were filled to obtain notched specimens. For these specimens, a third of the mold was filled and then vibrated for 5 seconds, a further third was filled and vibrated for 10 seconds and the final third was filled and vibrated for a further 15 seconds.

The top surfaces of the specimens were finished manually and then covered with a plastic sheet to prevent evaporation. The following day the specimens were demolded and placed under water.

Saw Cuts

After a period of 2 months, the specimens were cut using a vertical diamond band saw, firstly in the longitudinal direction (through the center) and secondly, in the transverse direction at the heights of 75 mm, 150 mm and 225 mm. A schematic representation of these cuts can be seen in Figure C.1.

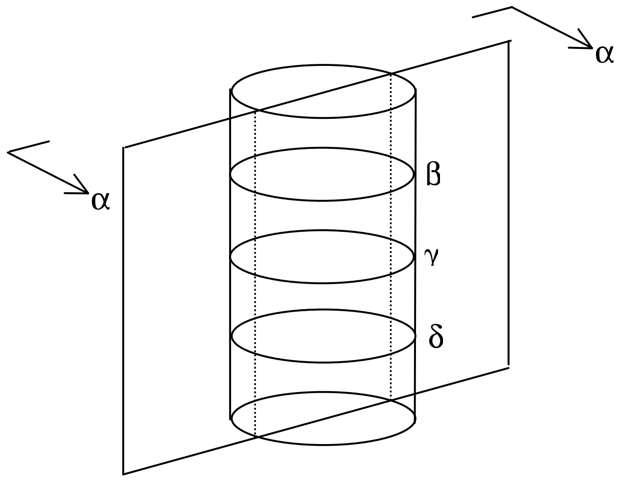

Figure C.1. Longitudinal (α) and transversal cuts (β, γ, δ)

Counting of the fibers

To count and record the number of fibers on the longitudinal cut, a grid comprising of 30×30 mm squares was used (Figure C.2a). The fibers in each square, on both faces of the longitudinal cut, were counted to eliminate errors in counting and discontinuity of fibers between the two sides, and the average of these values was calculated. On the transversal cuts, a circular template, which denoted several areas in annular domains of the surface, was used (Figure C.2b). The outer diameter of the domains A, B, C, D and E are 150 mm, 120 mm, 90 mm, 60 mm and 30 mm, respectively, as seen in Figure C.2c.

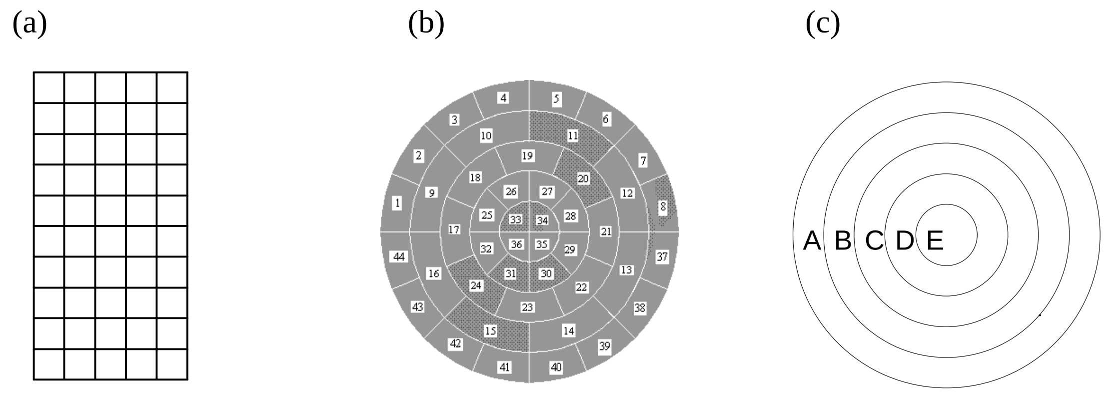

Figure C.2. Templates used for the (a) longitudinal and (b) (c) transversal cuts

C.3. Results and Analysis

In the specimens compacted with external vibration (table-vibration), visual observations of the cut surface did not reveal any segregation of aggregates or fibers. However, in the specimens compacted manually, some segregation of the coarse aggregates was observed. In the specimens with cast notches, the wall effect at the notch-tip was clearly seen with the existence of a zone rich in paste and poor in aggregates.

The fiber count on the longitudinal cuts are given in Table C.2 a-c for the three specimen types, along with the mean (and standard deviation), the percentage of fibers and the fiber density in each layer. It can be seen that the number of fibers varies significantly from one specimen to another, especially in the bottom third of the specimen. In all cases (see Fig. C.3), there is some segregation of the fibers with a significantly higher number of fibers in the bottom fifth than in the rest of the cut. In the tamped specimens, the top layer is markedly poorer in fibers than the rest of the specimen.

The mean density of fibers in the externally vibrated specimens is 0.63 fibers/cm^2 over the entire cut and is 0.55 fibers/cm^2 over the central three-fifths of the specimen. In the tamped specimens, the fiber density over the entire cut is 0.61 fibers/cm^2 and is 0.63 fibers/cm^2 over the central three-fifths of the specimen. In the notched specimens, a higher density of fibers is observed, probably due to the longer vibration time, especially for the lower part of the specimens.

Table C.2a. Compaction with external vibration (table) – longitudinal cut

Distance from the top (mm)	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	% of fibers	Density fibers/cm^2
0-60	60	42	70	57±14	20.0	0.63
60-120	55	44	59	53±8	18.5	0.58
120-180	39	50	57	49±9	17.1	0.54
180-240	32	63	46	47±16	16.4	0.52
240-300	111	63	67	80±27	28.0	0.88

Table C.2b. Compaction by tamping – longitudinal cut

Distance from the top (mm)	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	% of fibers	Density fibers/cm^2
0-60	24	33	26	28±5	10.2	0.31
60-120	56	59	43	53±9	19.1	0.58
120-180	79	53	56	63±14	22.7	0.70
180-240	32	68	68	56±21	20.2	0.62
240-300	84	86	61	77±14	27.8	0.85

Table C.2c. Notched specimens vibrated externally – longitudinal cut

Distance from the top (mm)	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	% of fibers	Density fibers/cm^2
0-60	74	84	43	67±21	18.2	0.74
60-120	58	58	72	63±8	17.1	0.70
120-180	67	62	61	63±3	17.1	0.70
180-240	85	68	72	75±9	20.4	0.83
240-300	93	90	116	100±14	27.2	1.11

Distance from the top (mm)	Table-vibration	Tamping	Notched specimen, table vibrated
0-60	57 (0.63f/cm^2)	28 (0.31f/cm^2)	67 (0.74f/cm^2)
60-120	53 (0.58f/cm^2)	53 (0.58f/cm^2)	63 (0.70f/cm^2)
120-180	49 (0.54f/cm^2)	63 (0.70f/cm^2)	63 (0.70f/cm^2)
180-240	47 (0.52f/cm^2)	56 (0.62f/cm^2)	75 (0.83f/cm^2)
240-300	80 (0.88f/cm^2)	77 (0.85f/cm^2)	100 (1.11f/cm^2)

Figure C.3. Mean number of fibers and fiber density (fibers/cm^2) at different heights

The fiber count on the transversal cuts (Fig. C.1) at different heights are given in the Tables C.3 a-c for the specimens compacted by external vibration, along with the mean (and standard deviation) and the fiber density in each layer. Similarly, the corresponding values for the tamped specimens are given in Tables C.4 a-c. It can be seen that the number of fibers does not vary significantly between specimens. Also, there does not appear to be any segregation of fibers in neither the radial direction nor between the different transversal cuts.

Table C.3a. Specimens compacted by external vibration (table) cut at 75 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	37	21	31	30±8	0.47
B	23	23	20	22±2	0.44
C	17	10	13	13±4	0.36
D	10	4	17	10±7	0.47
E (center)	8	3	4	5±3	0.70

Table C.3b. Specimens compacted by external vibration (table) cut at mid-height

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	26	26	30	27±3	0.42
B	32	13	32	26±11	0.53
C	8	6	24	13±10	0.36
D	22	9	22	18±8	0.85
E (center)	5	6	6	6±1	0.85

Table C.3c. Specimens compacted by extern. vibration (table) cut at 225 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	46	35	32	37±8	0.58
B	42	19	24	28±12	0.56
C	22	16	9	16±7	0.45
D	13	8	4	9±5	0.42
E (center)	3	1	4	3±2	0.42

Table C.4a. Hand tamped specimens cut at 75 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	21	19	25	22±3	0.34
B	42	25	33	34±9	0.69
C	25	19	25	23±4	0.65
D	8	7	9	8±1	0.37
E (center)	0	2	5	3±3	0.42

Table C.4b. Hand tamped specimens cut at mid-height

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	22	36	39	33±9	0.52
B	36	36	25	33±7	0.67
C	20	17	15	18±3	0.51
D	9	14	10	11±3	0.52
E (center)	3	6	5	5±2	0.70

Table C.4c. Hand tamped specimens cut at 225 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	33	42	33	36±6	0.56
B	23	17	28	23±6	0.46
C	19	21	14	18±4	0.51
D	10	9	7	9±2	0.42
E (center)	2	6	6	5±3	0.70

In the notched specimens, there is a higher density of fibers on the cut at 75 mm from the top (Table C.5a) compared to that at 225 mm from the top (Table C.5c). Moreover, it appears that on the notch plane (Table C.5b), there is a higher density of fibers, especially near the tip of the cast notch (i.e., Domain B).

Table C.5a. Notched specimens cut at 75 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	31	25	37	31±6	0.48
B	18	24	23	22±4	0.44
C	17	13	17	16±3	0.45
D	9	2	10	7±5	0.33
E (center)	1	1	8	4±4	0.56

Table C.5b. Notched specimens cut at mid-height, along the notch plane

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
B (notch-tip)	29	37	37	35±5	0.71
C	14	18	11	15±4	0.42
D	11	13	15	13±2	0.61
E (center)	1	3	2	2±1	0.28

Table C.5c. Notched specimens cut at 225 mm from the top

Domain	Specimen 1	Specimen 2	Specimen 3	No. of fibers (mean and std. dev.)	Density fibers/cm^2
A (surface)	30	19	34	28±8	0.44
B	20	13	17	17±4	0.34
C	12	21	9	14±7	0.39
D	6	10	5	7±3	0.33
E (center)	2	1	1	2±1	0.28

Table C.6 shows the mean fiber densities in the horizontal and vertical cuts for the three specimen types. For the table-vibrated case, it can be seen that there is some segregation of the fibers and that the fiber density in the middle of the specimen is higher in the vertical cut than in the transversal cuts. This indicates a slight preferential orientation of the fibers in the horizontal direction. In the tamped specimens, there is no clear evidence of segregation but, interestingly, the horizontal orientation is stronger.

In the notched specimens, which were compacted in three layers, the vibration time for the lower half of the specimen is more than that of the unnotched specimen. This probably explains the fact that there is much more anisotropy in the orientation, with a much higher fiber density on the vertical cuts than in the transversal cuts.

Table C.6. Mean fiber densities for the different cases

Compaction	Horizontal cuts				Vertical cuts	
	75 mm from top	mid-height	225 mm from top	Mean	entire height	Middle three-fifths
Table-vibrated	0.45	0.51	0.53	0.50	0.63	0.55
Tamped	0.51	0.57	0.52	0.53	0.61	0.63
Notched, table-vibrated	0.45	0.57	0.38	0.47	0.82	0.74

C.4. Conclusions

From the results of the present study, some basic conclusions can be derived, though the scope of the work is quite limited. Firstly, the cutting of specimens along the two principal directions and counting the fibers on the cut surfaces seems to be a simple and satisfactory method for evaluating the distribution and orientation of fibers in a specimen. It can, therefore, be used as a check against the effects of excessive vibration on laboratory specimens. When sufficient vibration is used, the non-uniformity and anisotropy of the fibers is limited, and comparable to that produced by manual tamping, which seems acceptable for concretes with good workability. The non-uniform fiber distributions observed in the notched specimens suggest that it is better to cut, rather than to cast, the notch.

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