Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.108.12

Differential characteristics of concrete in centrifugally spun and vibrospun building structures

L.R. Mailyan , ***S.A. Stel'makh*** , ***E.M. Shcherban'****

Don State Technical University, Rostov-on-Don, Russia

**E-mail: au-geen@mail.ru*

Keywords: concretes, mechanical properties, compressive strength, tensile strength, bending strength, elastic moduli, strain-stress curves

Abstract. This paper presents research into the variatropic structural characteristics of experimental circular-section concrete specimens as well as the related differential (varying depthwise) structural characteristics of concrete subjected to centrifugal spinning and vibrospinning. The researchers sought to assess how the production technology (centrifugal spinning or vibrospinning) could affect the differential (varying depthwise) characteristics of concrete: density; cube and prism axial compressive strength; ultimate axial compressive strain; axial tensile strength and tensile bending strength; ultimate axial tensile strain; the elastic modulus; the strain-stress curve for compression and tensioning. The researchers made and tested six basic centrifugally spun and vibrospun circular-section specimens that had an outer diameter D of 450 mm, an inner diameter d of 150 mm, and a total height H = 1200 mm. The manufacturing technology differed in the experiments, as the team used both centrifugal spinning and vibrospinning. Experimental research into the differential characteristics of centrifugally spun and vibrospun concrete aged 7, 28, and 180 days as exposed by compression and tension revealed that the outer concrete layer had the best characteristics, while the inner layer was the worst. The experiments thus back the three-layer model of the variatropic structure in centrifugally spun and vibrospun concrete. The following differentiation was observed in variatropic concrete: the outer layer had the best strength and elastic modulus, while being less deformable; the inner layer had the least strength and elastic modulus, while being more deformable; the mid-layer concrete was average in terms of everything. Stress-strain curves of centrifugally spun and vibrospun concrete did differ by layer, too, further proving that such concrete had a variatropic structure. The curves showed the greatest strength for the outer layer and the lowest for the inner layer, while the mid layer had average values.

1. *Introduction*

The physical fundamentals of variatropic structure in centrifugally spun concrete are detailed in [1–9]. The way it emerges essentially boils down to the fact that as the mold starts rotating at low rpm, the material is distributed evenly across the circular section; then, as the rotation accelerates, centrifuging squeezes some of the curing water out of the cement dough together with highly-dispersed particles; this brings larger filler particles closer together to condense the concrete mix.

Yu.Ya. Steyermann was the first to study the mechanism of filler drift in centrifugal condensing in detail. Assuming that the filler grains were suspended in the cement dough, he found that the dough exerted hydrodynamic pressure on the filler particles and quantified the distribution of fillers and cement dough across the section [8].

Mailyan, L.R., Stel'makh, S.A., Shcherban', E.M. Differential characteristics of concrete in centrifugally spun and vibrospun building structures. Magazine of Civil Engineering. 2021. 108(8). Article No. 10812. DOI: 10.34910/MCE.108.12

Later, I.N. Akhverdov showed that this pressure depended on the geometric size of the spun product as well as on the mold rotation speed. The pressure alters depthwise in the wall: it is the lowest on the inner surface and peaks on the outer surface, which affects the specifics of how the liquid is being squeezed out of the concrete mix. The characteristic uneven depthwise distribution of cement dough in the product is associated with the emergence of multiple directed radial filtration channels increasing cross-section and number towards the inner surface. This is why the inner slurry layer of a concrete circle has a very high porosity [1].

Some other authors have shown that when using a mix of filler grains different in average density, properly attuned centrifuging speeds can produce more even, and thus more desirable depthwise distribution of those grains, as it is the unevenness of distribution that destabilizes the physical and mechanical properties [3, 4, 6, 7].

Research into the strength of centrifugally spun concrete has found that physical and mechanical properties differ significantly in inner and outer layers of concrete circles. These results not only prove that a single centrifugally spun specimen may differ physically and mechanically layer from layer; they also show that such concrete does differ from its vibrospun counterparts in terms of such properties [4, 6, 7].

V.M. Batashev and S.T. Androsov studied the strain-related properties of centrifugally spun concrete: the elastic moduli, the parametric points of microfracturing, creep, and shrinkage. The strengths of centrifugally spun concrete are scale-dependent, which is why it is important that experimental specimens be made under such conditions that mimic the real-world setting as much as possible. The strain-related properties of centrifugally spun concrete differ significantly depthwise in a circular section, as the inner layers have greater shrinkage and compressibility. Difference in properties may also depend on the specimen age; thus, layers may differ in strain by 50...100 % in freshly made concrete, 20...40 % after 50...60 days [2].

When in use, centrifugally spun concrete products are exposed to volatile stress and strain due to the uneven temperature and humidity fields emergent in the concrete body.

V.I. Podolsky [5] has found that the closed circle of a centrifugally spun reinforced-concrete pole carries two types of forced strain that determine the emergence of stresses:

– inner strain that occurs regardless of the element's static diagram due to the curvilinear distribution of moisture across over the cross-section;
– forced strain that occurs in a closed circle due to strain being limited along the entire outline or in a section of it.

Cyclical moistening and drying causes significant shrinkage-related strain that contributes to fracturing.

The way centrifugally spun concrete resists periodic freezing and thawing also has some specifics pertaining to the structural heterogeneity or variatropy of the material [10, 11].

It can be assumed that sequential molding layer-by-layer or use of associated vibration in centrifuging can direct the structuring of variatropic centrifugally spun concrete [12].

Today's research focuses more and more on circular-section reinforced-concrete products of variatropic structure; when exposed to a variety of impacts, such products cannot be modeled by conventional calculations as their stress-strain state is far more complex [13–15]. Papers [1–9] present the fundamentals behind the existing methods for calculating the parameters of centrifugally spun reinforced-concrete circular-section structures.

For instance, these methods can be used to calculate the parameters of circular-section reinforced-concrete products in a variety of stress-strain states [16–18].

G.A. Aksomitas researched short centrifugally spun circular-section columns that contained direct-axis reinforcements; the columns were exposed to short-term compression [9].

Centrifugal spinning and vibrospinning induce significantly different centrifugal and centripetal forces acting on outer, mid, and inner layers of the cross-section; this in turn induces a significant difference in the structure and characteristics of concrete in these layers, which must be taken into consideration when calculating [10–23].

This paper presents research into the variatropic structural characteristics of experimental circular-section concrete specimens as well as the related differential (varying depthwise) structural characteristics of concrete subjected to centrifugal spinning and vibrospinning.

The purpose of the work is to study concretes of a variatropic structure, vibrocentrifuged structures made of them with concrete characteristics differing in cross-section, and to develop recommendations for the design assessment of concrete characteristics and the operation of structures.

Research objectives:

- to investigate the differential (differing in cross-section) design characteristics of centrifuged and vibro-centrifuged concretes of variatropic cross-sections;
- to propose theoretical recommendations for the design determination of the structural characteristics of centrifuged and vibrocentrifuged concretes, taking into account variatropy.

The object of research is centrifuged and vibrocentrifuged concretes of variatropic structure and compressed elements from them.

The subject of research is the structural characteristics of variatropic concretes and taking into account the variatropicity in the calculation and design of compressed reinforced concrete elements from them.

2. Methods

The researchers made and tested six basic centrifugally spun and vibrospun circular-section specimens that had an outer diameter D of 150 mm, an inner diameter d of 1200 mm, and a total height H = 1200 mm.

For equipment and methods, see [24–28]. The manufacturing technology differed in the experiments, as the team used both centrifugal spinning (designated as C hereinafter) and vibrospinning (V).

After the analysis of scientific data, the following were accepted for research:

- crushed stone granite JSC "Pavlovsk Nerud" fraction 5-20 mm;
- quartz sand of the Grushevskoye deposit (M_k = 2.0).

As a binder, we used no additives Portland cement Evrocement of the group "Oskolcement" grade 500 normally hardening, the physical and mechanical properties of which are presented in Table 1.

Table 1. Physical and mechanical properties of cement.

Name	Specific surface, m^2/kg	Normal density, %	Setting time, hours-min.		Activity, MPa	
			start	end	R_b	R_{bt}
Portland cement	365	25.5	1-05	3-15	5.9	51.5

The researchers sought to assess how the production technology (centrifugal spinning or vibrospinning) could affect the differential (varying depthwise) characteristics of concrete: density; cube and prism axial compressive strength; ultimate axial compressive strain; axial tensile strength and tensile bending strength; ultimate axial tensile strain; the elastic moduli; the stress-strain curve for compression ($\sigma_b - \varepsilon_b$) and tension $\sigma_{bt} - \varepsilon_{bt}$).

The test methodology differed in a sense that each basic experimental specimen was subjected to multiple different tests. Each basic specimen was tested aged 7, 28, and 180 days.

A quadrant was outlined in the specimen section that was further split into three layers (outer, mid, and inner), each 5 cm thick; then the layer-specific characteristics were found, see Fig. 1 and 2.

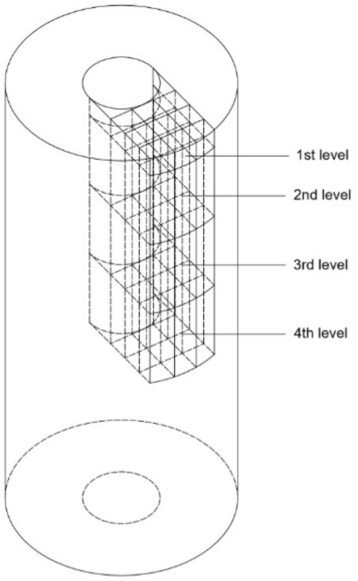


Figure 1. Diagram of taking small-size concrete samples for testing the depthwise differential characteristics of the basic full-size circular-section specimens.

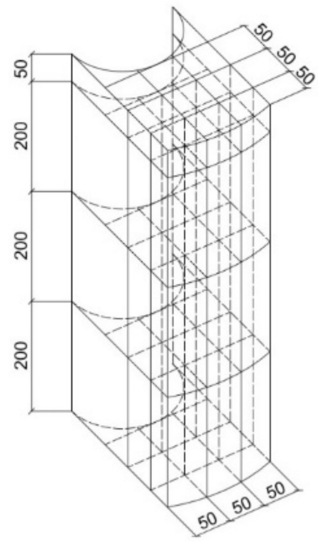


Figure 2. Experimental small-size concrete samples taken from experimental basic full-size circular-section specimens to test their differential characteristics.

For axial compression and tension tests, 9 cubes sized 5×5×5 cm were saw-cut out of the quadrant along the entire specimen (Level 1, axial compression tests), and so were 9 prisms sized 5×5×20 cm (Level 2, bending tension tests), 9 prisms sized 5×5×20 cm (Level 3, axial compression tests), and an additional 9 prisms sized 5×5×20 cm (Level 4) for axial tension tests.

Cube-based axial compression tests returned the values $R_{b,cub,i}$, prism-based axial compression tests returned the values $R_{b,i}$, $\varepsilon_{bR,i}$, $R_{bt,i}$, $\varepsilon_{btR,i}$, $E_{b,I} = E_{bt,i}$ as well as the stress-strain curves $\sigma_{b,i} – \varepsilon_{b,i}$, while prism-based axial tension tests returned $R_{bt,i}$ and $\sigma_{bt,i} – \varepsilon_{bt,I}$, and the prism-based bending tension tests returned $R_{btb,i}$.

All the specimens were tested aged 7, 28, and 180 days as required by Russian State Standard GOST 10180. Scaling factor was applied to correctly compare samples of different size.

Tests were carried out in accordance with Russian State Standard GOST 10180: an IPS-10 press was used for axial compressive tests of prisms, while a special unit based on a P-10 test press was used for axial tensile tests of prisms.

Strain in concrete was measured by a chain of tensor sensors with a base of 50 mm and clock-type indicators graduated at 0.001 mm.

Tests were carried out at a constant straining rate to derive not only the strength and strain-related characteristics of concrete, but also its complete stress-strain curves $\sigma - \varepsilon$ with descending branches. To that end, the experiments involved not only tensometers but also oscillographs.

The load would first increase until hitting the peak value, then decrease while the strain continued to increment. Thus, the tests recorded the descending branch of the stress-strain curve, which in this study had fairly stable outline up to σ = 0.8 R in both stress and strain, then turned volatile.

Below are the test variables:

- manufacturing technology: centrifugal spinning and vibrospinning;
- stress-strain type: axial compression and axial tension;
- sample type: 5×5×5 cm and 15×15×15 cm cubes, 5×5×20 cm and 15×15×60 cm prisms;
- test mode: constant loading rate or constant straining rate;
- concrete age: 7, 28, or 180 days.

Centrifugally spun and vibrospun specimens were variatropic depthwise, i.e. they could be conditionally split into multiple layers that differed in material properties due to the manufacturing technology.

To detect how layers differed in terms of properties, a Pulsar 2.2 unit was used for preliminary ultrasonic scanning. To that end, 3 prisms sized 1200×150×50 mm were conventionally outlined in the wall of each specimen. The unit's sensors were attached as shown in Fig. 3 in all the three conventional layers (inner, mid, and outer) of the variatropic structure across the wall.

Declared concrete class – B40.

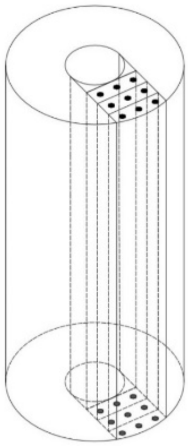


Figure 3. Ultrasonic sensor locations.

3. Results and Discussion

Table 2 shows the qualitative and quantitative distribution of density and strength in centrifugally spun and vibrospun concrete.

Table 2. The results of ultrasonic scanning of experimental specimens.

Indicator	Technology					
	Centrifugal spinning			Vibrospinning		
	Layer			Layer		
	outer	mid	inner	outer	mid	inner
Density	2495	2403	2316	2544	2492	2396
Compressive strength, MPa	43.4	35.5	32.2	68.2	65.1	41.6
Elastic moduli, MPa	34.3	27.8	24.8	38.8	35.2	28.5

As shown in Table 2, the outer layer had the greatest strength regardless of the manufacturing technology, as it was exposed to maximum centrifugal force; the inner layer was the weakest.

For centrifugally spun concrete, the curve of strength as a function of layer (from the outer to the inner layer) is a curve that slopes down and has downward concavity as shown in Fig. 4, while for vibrospun concrete, the concavity faces up, see Fig. 5.

That being said, the mid layer is between its inner and outer counterparts in terms of strength, which is below the arithmetic mean of inner+outer layer in centrifugally spun concrete but above that in vibrospun concrete, hence the difference in concavity.

The experiments thus back the three-layer model of the variatropic structure in centrifugally spun and vibrospun concrete.

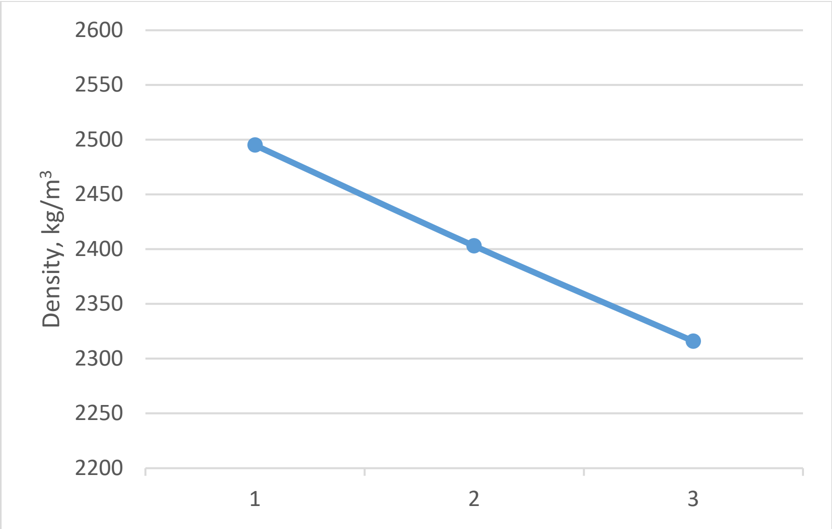
Similar changes are observed in layer strain and elastic moduli. It is the outer layer that should have the greatest elastic moduli, while the inner layer should have the lowest elastic moduli, with that of the mid layer being in between, slightly below average in centrifugally spun concrete and slightly above in vibrospun concrete, as evidenced in [4, 7] for centrifuged concrete.

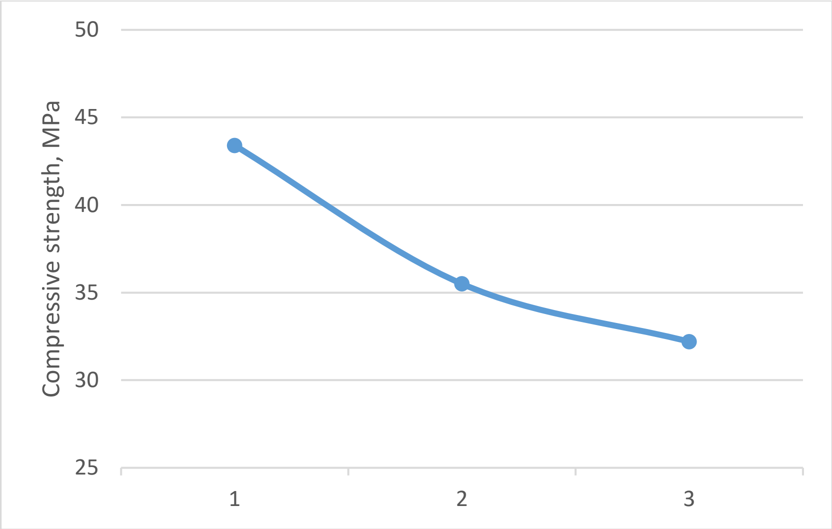
Accordingly, all this causes the difference in the $\sigma - \varepsilon$ curves for different concrete layers.

Mechanical tests prove that, see below.

The 5 cm inner, mid, and outer layers were compared against each other in terms of compressive and tensile strength.

Conclusions were drawn from the analysis of experimentally found strength (Table 3) and its deviations (Table 4) shown in Fig. 6 for compression and in Fig. 7 for tension.





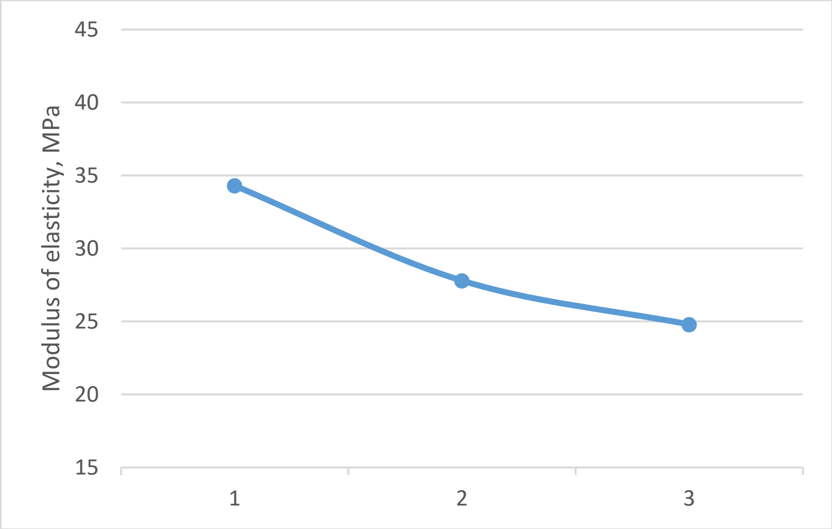
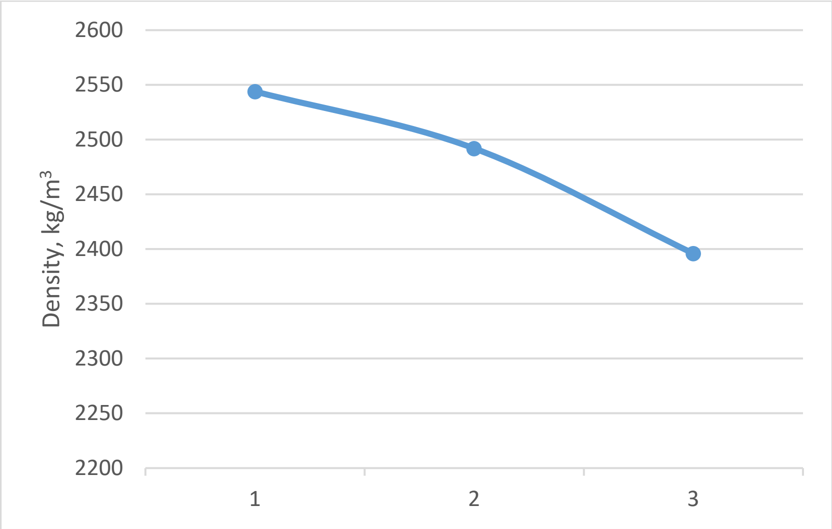
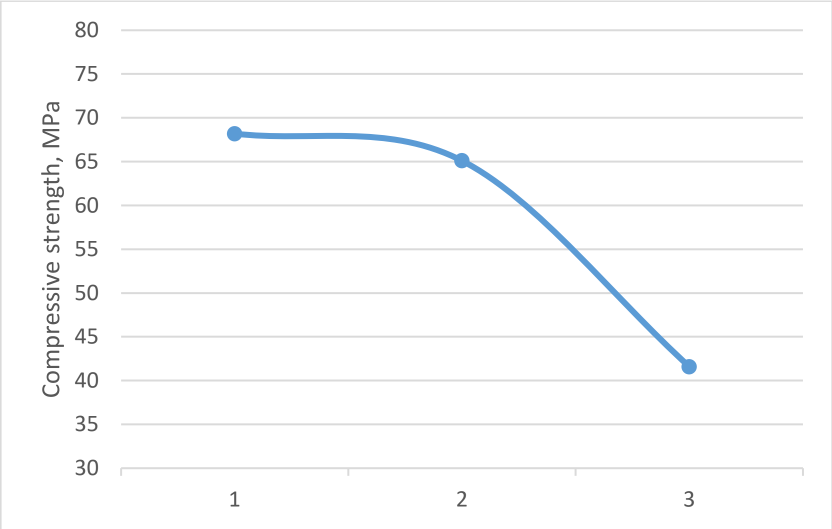


Figure 4. Layer-by-layer distribution of density, strength, and elastic moduli in centrifugally spun concrete: 1 is for the outer layer; 2 is for the mid layer; 3 is for the inner layer.





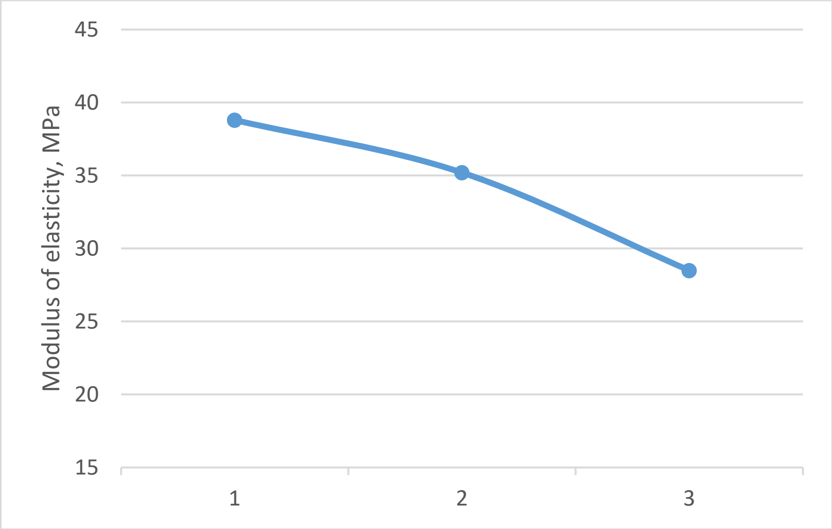


Figure 5. Layer-by-layer distribution of density, strength, and elastic moduli in vibrospun concrete: 1 is for the outer layer; 2 is for the mid layer; 3 is for the inner layer.

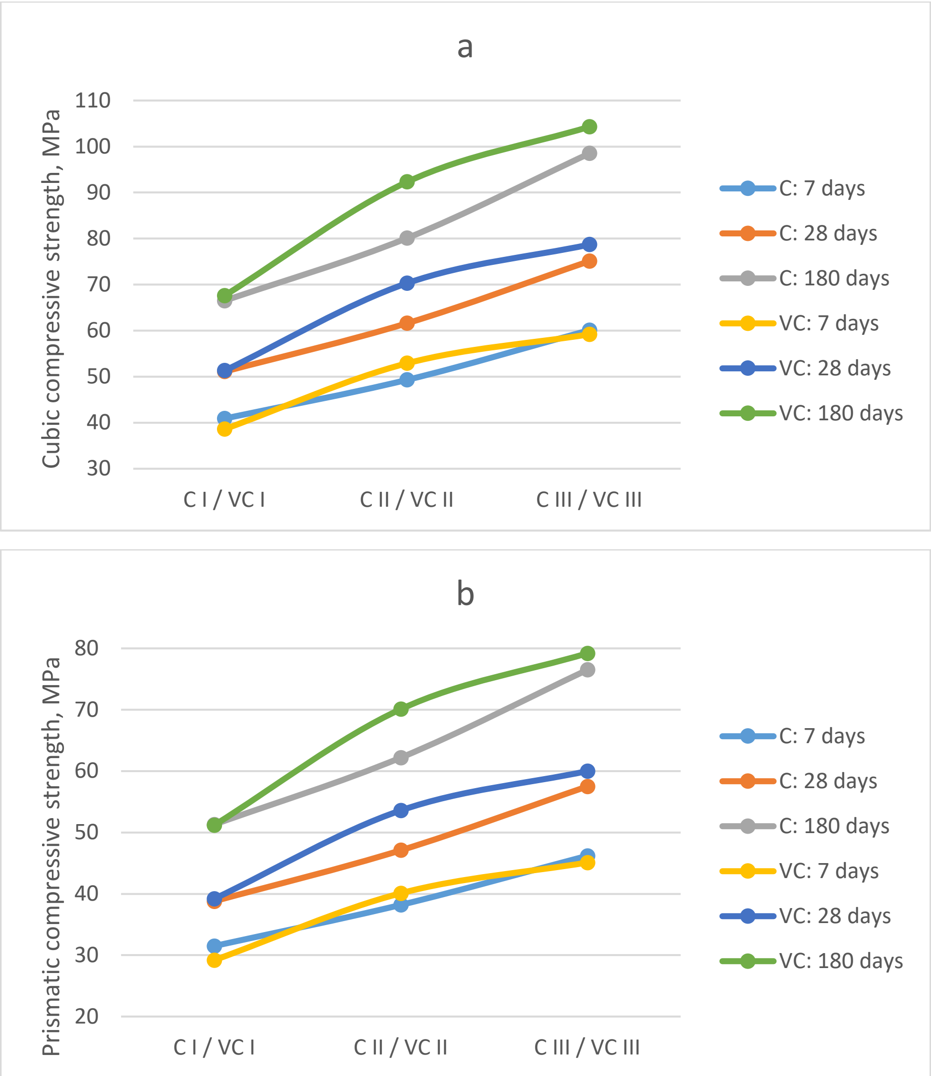


Figure 6. Compressive strength of centrifugally spun (C) and vibrospun (V) concrete: (a) cubes; (b) prisms.

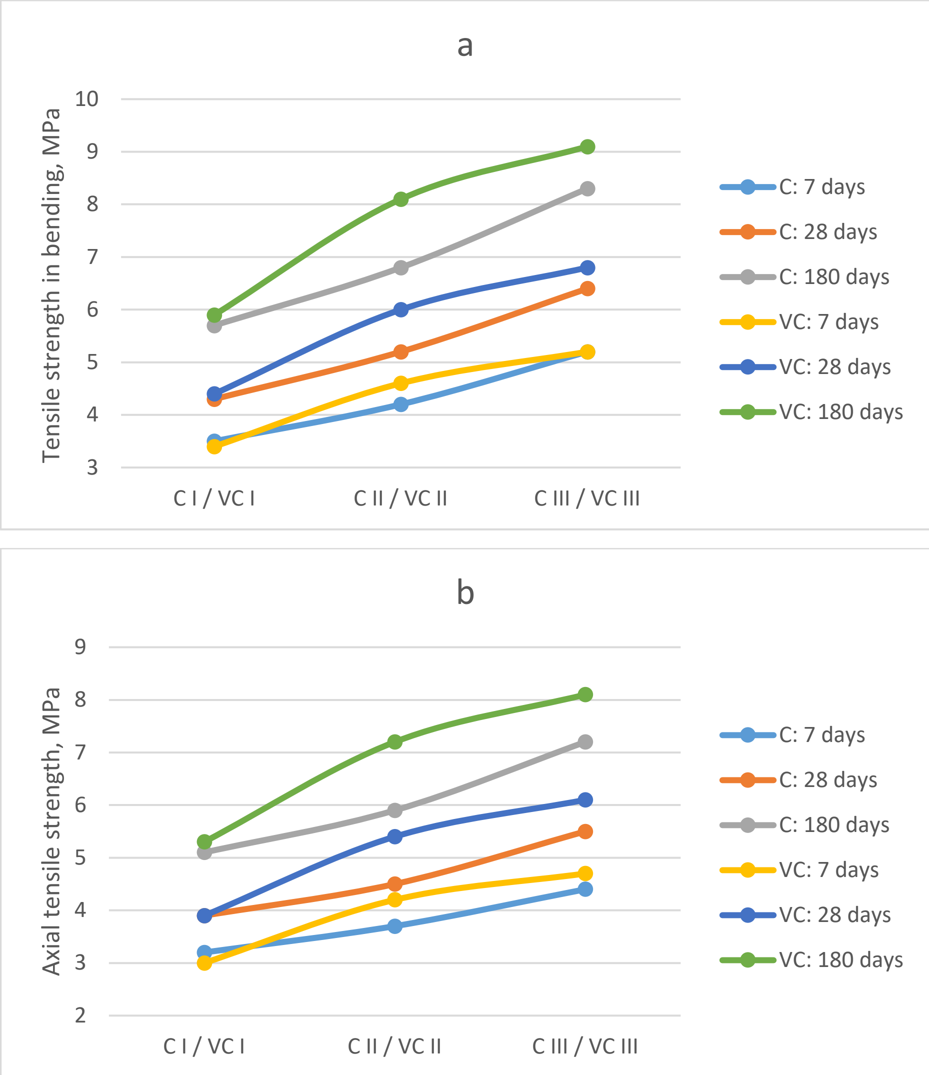


Figure 7. Tensile strength of centrifugally spun (C) and vibrospun (V) concrete: (a) bending; (b) axial.

Table 3. Experimental differential characteristics of variatropic structural layers in centrifugally spun and vibrospun concrete.

Characteristics of concrete	Manufacturing technology					
	Centrifugal spinning (C)			Vibrospinning (V)		
	Layers			Layers		
	inner CI	mid CII	outer CIII	inner VI	mid VII	outer VIII
Density, kg/m^3	2342/2335/2319	2443/2432/2411	2502/2495/2470	2350/2344/2329	2466/2455/236	2515/2502/277
Compressive strength, MPa: (a) cubes (b) prisms	40.9/51.1/66.5 31.5/38/8/51.3	49.3/61.6/80.1 38.2/47.1/62.2	60.1/75.1/98.5 46.2/57.5/76.5	38.6/51.3/67.6 29.2/39.2/51.2	52.9/70.3/92.3 40.1/53.6/70.1	59.2/78.7/104.3 45.1/60.0/79.2
Tensile strength, MPA: (a) bending (b) axial	3.5/4.3/5.7 3.2/3.9/5.1	4.2/5.2/6.8 3.7/4.5/5.9	5.2/6.4/8.3 4.4/5.5/7.2	3.4/4.4/5.9 3.0/3.9/5.3	4.6/6.0/8.1 4.2/5.4/7.2	5.2/6.8/9.1 4.7/6.1/8.1
Ultimate axial compressive strain, mm/m*10-3	3.40/2.64/2.10	2.80/2.15/1.72	2.35/1.82/1.45	3.10/2.40/1.80	2.80/2.12/1.61	2.00/1.54/1.17

Characteristics of concrete	Manufacturing technology					
	Centrifugal spinning (C)			Vibrospinning (V)		
	Layers			Layers		
	inner CI	mid CII	outer CIII	inner VI	mid VII	outer VIII
Ultimate axial tensile strain, mm/m*10-4	1.97/1.48/1.35	1.60/1.20/1.05	1.38/1.04/0.90	1.64/1.30/1.00	1.49/1.14/0.90	1.10/0.83/0.65
Elastic moduli, MPa	19.6/23.9/31.3	22.5/27.8/36.4	27.2/33.9/44.8	16.8/21.6/28.0	22.8/29.2/38.2	25.7/33.0/43.1

Note. Slash separates the values at 7, 28, and 180 days of age.

Table 4. Deviations in differential characteristics of variatropic structural layers in centrifugally spun and vibrospun concrete.

Characteristics of concrete	Deviations, %								
	C			V			V — C		
	Layers			Layers			Layers		
	Δ1	Δ2	Δ3	Δ4	Δ5	Δ6	Δ7	Δ8	Δ9
Density, kg/m3	4.3/4.2/ 4.0	2.4/2.6/ 2.4	6.8/6.9/ 6.5	4.9/4.7/ 4.6	2.0/1.9/ 1.7	7.0/6.7/ 6.4	0.3/0.4/ 0.4	0.9/0.9/ 1.0	0.5/0.3/ 0.3
Compressive strength, MPa: (a) cubes (b) prisms	20.5/ 20.5/ 20.5 21.3/ 21.4/ 21.2	21.9/ 21.9/ 23.0 20.9/ 22.1/ 23.0	46.9/ 47.0/ 48.1 46.7/ 48.2/ 49.1	37.0/ 37.0/ 36.5 37.3/ 36.7/ 36.9	11.9/ 11.9/ 13.0 12.5/ 11.9/ 13.0	53.4/ 53.4/ 54.3 54.5/ 53.1/ 54.7	5.6/ 0.4/ 1.7 7.3/ 1.0/ 0.2	7.3/ 14.1/ 15.2 5.0/ 13.8/ 12.7	1.5/ 4.8/ 5.9 2.4/ 4.3/ 3.5
Tensile strength, MPA: (a) bending (b) axial	20.0/ 20.9/ 19.3 15.6/ 15.4/ 15.7	23.8/ 23.1/ 22.1 18.9/ 22.2/ 22.0	48.6/ 48.8/ 45.6 37.5/ 41.0/ 41.2	35.3/ 36.4/ 37.3 40.0/ 38.5/ 35.8	13.0/ 13.3/ 12.3 11.9/ 13.0/ 12.5	52.9/ 54.5/ 54.2 56.7/ 56.4/ 52.8	2.9/ 2.3/ 3.5 6.3/ 0.0/ 3.9	9.5/ 15.4/ 19.1 13.5/ 20.0/ 22.0	0.0/ 6.2/ 9.6 6.8/ 10.9/ 12.5
Ultimate axial compressive strain, mm/m*10-3	17.65/ 18.56/ 18.10	16.07/ 15.35/ 15.70	30.88/ 31.06/ 30.95	9.68/ 11.67/ 10.56	28.57/ 27.36/ 27.33	35.48/ 35.83/ 35.00	8.82/ 9.09/ 14.29	0.00/ 1.40/ 6.40	14.89/ 15.38/ 19.31
Ultimate axial tensile strain, mm/m*10-4	18.78/ 18.92/ 22.22	13.75/ 13.33/ 14.29	29.95/ 29.73/ 33.33	9.15/ 12.31/ 10.00	26.17/ 27.19/ 27.78	32.93/ 36.15/ 35.00	16.75/ 12.16/ 25.93	6.88/ 5.00/ 14.29	20.29/ 20.19/ 27.78
Elastic moduli, MPa	14.8/ 16.3/ 16.3	20.9/ 21.9/ 23.1	38.8/ 41.8/ 43.1	35.7/ 35.2/ 36.4	12.7/ 13.0/ 12.8	53.0/ 52.8/ 53.9	14.3/ 9.6/ 10.5	1.3/ 5.0/ 4.9	5.5/ 2.7/ 3.8

Notes: slash separates the values at 7, 28, and 180 days of age.

$$\Delta_1 = \frac{C_{II} - C_I}{C_I} \cdot 100\%;\ \ \Delta_2 = \frac{C_{III} - C_{II}}{C_{II}} \cdot 100\%;\ \ \Delta_3 = \frac{C_{III} - C_I}{C_I} \cdot 100\%;$$

$$\Delta_4 = \frac{VC_{II} - VC_I}{VC_I} \cdot 100\%;\ \ \Delta_5 = \frac{VC_{III} - VC_{II}}{VC_{II}} \cdot 100\%;\ \ \Delta_6 = \frac{VC_{III} - VC_I}{VC_I};$$

$$\Delta_7 = \frac{VC_I - C_I}{C_I} \cdot 100\%;\ \ \Delta_8 = \frac{VC_{II} - C_{II}}{C_{II}} \cdot 100\%;\ \ \Delta_9 = \frac{VC_{III} - C_{III}}{C_{III}} \cdot 100\%.$$

Vibrospun concrete has virtually the same patterns of layer-by-layer compressive strength distribution, although slightly less pronounced qualitatively: while in variatropic centrifugally spun concrete, the curve of strength as a function of layer was slightly concave downwards, it was concave upwards for the vibrospun counterpart.

The same pattern was observed with respect to tensile strength.

The outer layer had 18.9 %/23.8 % greater axial and bending strength than the mid layer in centrifugally spun concrete. The mid layer was 15.7 %/20.9 % stronger than the inner one.

As of vibrospun concrete, its mid layer had slightly greater values of both types of tensile strength; the outer layer, too, was stronger than that of centrifugally spun concrete, while the inner layer was low compared to either of the others.

This analysis makes clear that when designing a structure, the variatropic nature of sections and the associated changes in concrete strength have to be taken into account.

The next step was to find how it could affect the layer-specific compressive and tensile strain. The outer layer had the lowest ultimate tensile and compressive strain, the inner layer had the highest values, and the mid layer was in between, slightly above average in centrifugally spun concrete and below average in vibrospun concrete, see Fig. 8 and 9.

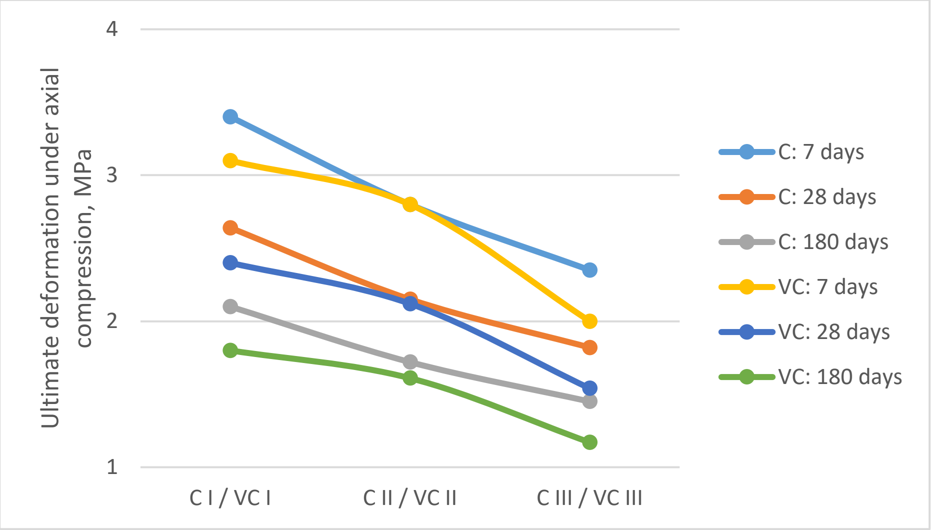


Figure 8. Ultimate compressive strain as a function of variatropic layer in centrifugally spun (C) and vibrospun (V) concrete.

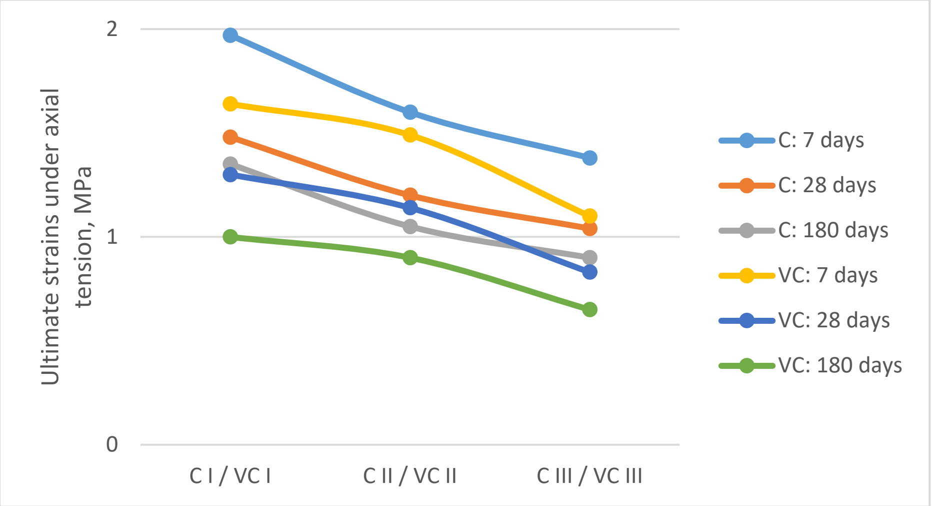


Figure 9. Ultimate tensile strain as a function of variatropic layer in centrifugally spun (C) and vibrospun (V) concrete.

It was the outer layer that had the greatest elastic moduli, while the inner layer had the lowest elastic moduli, with that of the mid layer being in between, slightly below average in centrifugally spun concrete and slightly above in vibrospun concrete, see Fig. 10.

The same applies to compressive and tensile elastic moduli, which did not differ significantly.

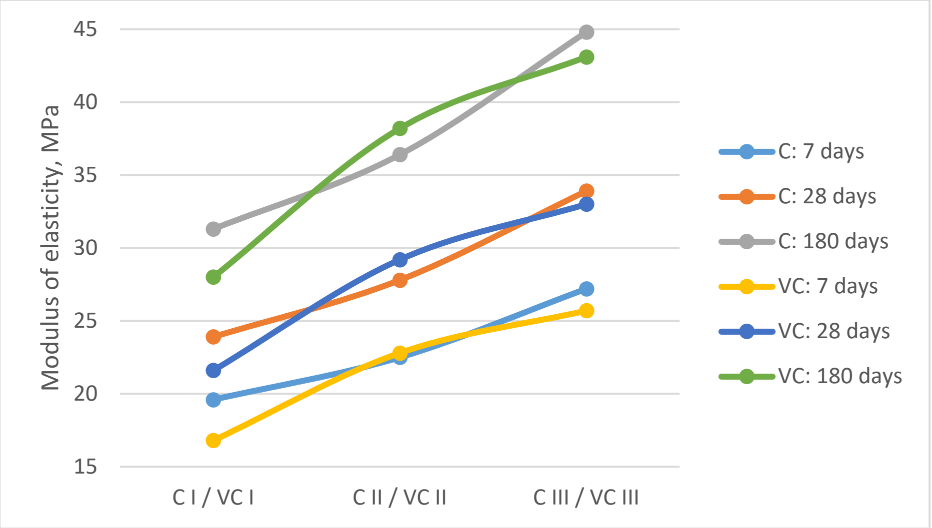


Figure 10. Elastic moduli as a function of variatropic layer in centrifugally spun (C) and vibrospun (V) concrete.

Accordingly, all this caused the difference in the $\sigma - \varepsilon$ curves for different concrete layers. Fig. 11 shows three experimental curves for inner, mid, and outer layers, where the difference matches the patterns observed for strength and strain-related characteristics.

For centrifugally spun concrete, it was the inner layer that had the lowest and shallowest $\sigma - \varepsilon$ curve associated with the lowest strength, the greatest associated ultimate strain, and the lowest elastic moduli that in such curves manifests itself as a bulge in the curve.

On the contrary, the outer layer that featured the greatest strength, the smallest ultimate strain, and a greater elastic moduli, the $\sigma - \varepsilon$ curve peaked at a more northwestern point with a more dramatic uprise in the ascending segment and a more drastic decline in the the descending segment.

The mid-layer curve is in between, closer to that of the inner layer.

Similar patterns are observable in case of vibrospun concrete. The only thing to note here is that the inner/outer layer curves differ even more drastically, while the mid-layer curve is closer to its outer-layer counterpart.

Fig. 1 shows the experimental $\sigma - \varepsilon$ curves.

To sum it up, the results are as follows.

First, the curves do differ layer-by-layer, whether the concrete is centrifugally spun or vibrospun, proving both structurally variatropic.

Secondly, the greatest strength (the Y-axis) was observed for the outer layer, and the lowest was shown by the inner layer regardless of the concrete technology.

Thirdly, the greatest strain (the X-axis) was observed for the inner layer, while the outer layer showed the least strain, also regardless of the concrete technology.

Fourthly, the greatest uprise (the elastic moduli) was seen in the outer-layer strain curves, and the lowest was found in the inner-layer curves.

Fifthly, whether for centrifugally spun or vibrospun concrete, the mid layer had average values, being closer to the arifmetic means for the former and closer to the outer-layer strain curves for the latter.

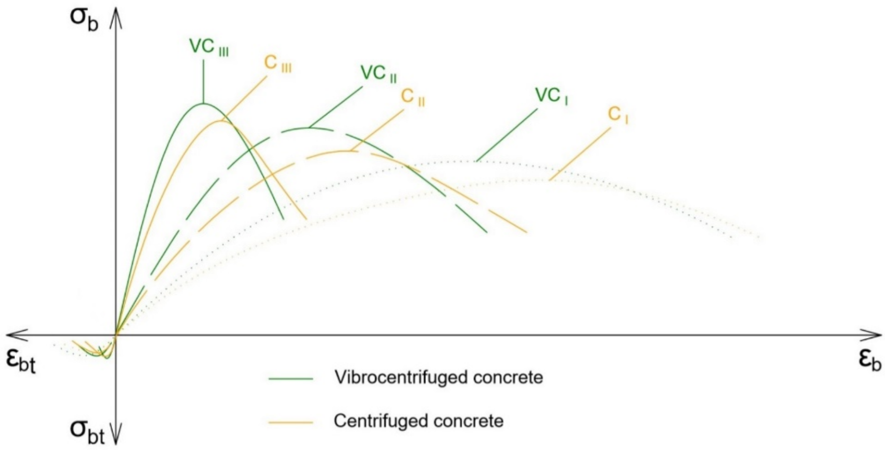


Figure 11. Transformation of variatropic layer-specific $\sigma - \varepsilon$ curves of centrifugally spun and vibrospun concrete.

Above is the analysis of how strength and strain-related characteristics changed from layer to layer in centrifugally spun and vibrospun concrete aged 28 days. However, concrete specimens were also tested aged 7 and 180 days.

The analysis generally shows that both types of concrete are immediately variatropic regardless of their age. In other words, the qualitative patterns of strength and strain-related differential characteristics did not change with age.

However, the quantitative indicators did, as concrete grew stronger with age.

The 7-day compressive and tensile strength was 73...81 % of the 28-day value. The corresponding ultimate strain was 21...29 % higher. The elastic moduli was 13...17 % lower.

At the age of 180 days, concrete had 11...13 % greater compressive and tensile strength, 9...12 % lower ultimate strain, and up to 15 % greater elastic moduli, although these changes are generally not as significant.

Accordingly, the age affected the stress-strain curves: compared to the 28-day curves, the 7- and 180-day counterparts differed in uprise, shallowness, and peak shift, see Fig. 12.

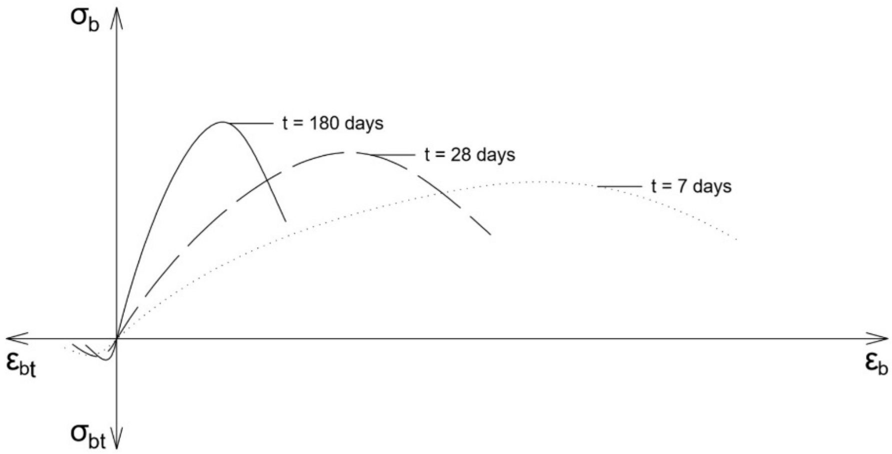


Figure 12. Fundamental changes in compressive and tensile strain curves at different ages of concrete.

4. Conclusion

The following conclusions were drawn.

Experimental research into the differential characteristics of centrifugally spun and vibrospun concrete aged 7, 28, and 180 days as exposed by compression and tension reveled that the outer concrete layer had the best characteristics, while the inner layer was the worst.

The experiments thus back the three-layer model of the variatropic structure in centrifugally spun and vibrospun concrete. The following differentiation was observed in variatropic concrete: the outer layer had the best strength and the elastic moduli, while being less deformable; the inner layer had the least strength and elastic moduli, while being more deformable; the mid-layer concrete was average in terms of everything.

Stress-strain curves of centrifugally spun and vibrospun concrete did differ by layer, too, further proving that such concrete had a variatropic structure. The curves showed the greatest strength for the outer layer and the lowest for the inner layer, while the mid layer had average figures.

Thus, the analysis of variatropy and differential characteristics of centrifugally spun and vibrospun concrete structures leads to a conclusion that such characteristics mostly have to be taken into account in calculations.

References

1. Akhverdov, I.N. Osnovy fiziki betona [Fundamentals of concrete physics]. Moscow: Stroyizdat, 1981. 464 p. (rus)
2. Batashev, V.M. Issledovanie prochnosti i deformatsii zhelezobetonnykh elementov kol'tsevogo secheniya pri izgibe, szhatii i rastyazhenii [The study of the strength and deformation of reinforced concrete elements of the annular cross section during bending, compression and tension]. Trudy instituta Energoset'proekt. 1975. 6. Pp. 70–86. (rus)
3. Dmitriev, S.A., Batashev, V.M. Deformatsii (progiby) zhelezobetonnykh elementov kol'tsevogo secheniya i raskrytie treshchin v nikh [Deformations (deflections) of reinforced concrete elements of annular cross-section and crack opening in them] // V sb.: Osobennosti deformatsii betona i zhelezobetona i ispol'zovanie EVM dlya otsenki ikh vliyaniya na povedenie konstruktsii [Features of the deformation of concrete and reinforced concrete and the use of computers to assess their impact on structural behavior]. Moscow: Stroyizdat, 1969. Pp. 157–189. (rus)
4. Petrov, V.P. Tekhnologiya i svoistva tsentrifugirovannogo betona s kombinirovannym zapolnitelem dlya stoek opor kontaktnoi seti: dis. … kand. tekhn. nauk [Technology and properties of centrifuged concrete with combined aggregate for racks of supports of the contact network: dis. ... cand. tech. of sciences]. Rostov-on-Don: RCEI, 1983. 175 p. (rus)
5. Podolsky, V.I. Zhelezobetonnye opory kontaktnoi seti. Konstruktsiya, ekspluatatsiya, diagnostika [Reinforced concrete supports of the contact network. Design, operation, diagnostics]. Moscow: Intekst, 2007. 152 p. (rus)
6. Romanenko, E.Yu., Trubitsin, M.A. Sposoby povysheniya nadezhnosti tsentrifugirovannykh opor kontaktnoi seti [Ways to improve the reliability of centrifuged supports of the contact network]. Inženernyj vestnik Dona (Rus). 2018. 1 [Online]. URL: http://www.ivdon.ru/ru/magazine/archive/n1y2018/4680 RU (reference date: 15.05.2020). (rus)
7. Radzhan, S. Svoistva tsentrifugirovannogo betona i sovershenstvovanie proektirovaniya tsentrifugirovannykh zhelezobetonnykh stoek opor LEP: dis. ... kand. tekhn. nauk [The properties of centrifuged concrete and the improvement of the design of centrifuged reinforced concrete pillars of power transmission towers: dis. ... cand. tech. of sciences]. Rostov-on-Don: RSUCE, 1997. 267 p. (rus)
8. Steyermann, Yu.Ya. Tsentrifugirovannyi beton [Centrifuged concrete]. Tiflis: Tekhnika da Shroma, 1933. 107 p. (rus)
9. Aksomitas, G.A. Prochnost' korotkikh tsentrifugirovannykh kolonn kol'tsevogo secheniya s prodol'noi armaturoi klassa At-V pri kratkovremennom szhatii: dis. … kand. tekhn. nauk [The strength of short centrifuged columns of annular cross-section with longitudinal reinforcement of class At-V during short-term compression: dis. ... cand. tech. of sciences]. Vilnius: VCEI, 1984. 261 p. (rus)
10. Aktham, H.A., Bunnori, N.M., Ahmed, T.N., Majid, T.A. Durability performance of a novel ultra-high-performance PET green concrete (UHPPGC). Construction and Building Materials. 2019. No. 209. Pp. 395–405.
11. Tasevski, D., Ruiz, M.F., Muttoni, A. Compressive strength and deformation capacity of concrete under sustained loading and low stress rates. Journal of Advanced Concrete Technology. 2018. No. 16. Pp. 396–415.
12. Ferrotto, M.F., Fischer, O., Cavaleri, L. Analysis-oriented stress–strain model of CRFP-confined circular concrete columns with applied preload. Mater Struct. 2018. 51 (44) [Online]. URL: https://doi.org/10.1617/s11527-018-1169-0 (date of application: 18.05.2020).
13. Maruyama, I., Lura, P. Properties of early-age concrete relevant to cracking in massive concrete. Cement and Concrete Research. 2019. 123(105770) [Online]. URL: https://doi.org/10.1016/j.cemconres.2019.05.015 (date of application: 18.05.2020).
14. Kim, J.-J., Yoo, D.-Y. Effects of fiber shape and distance on the pullout behavior of steel fibers embedded in ultra-high-performance concrete. Cement and Concrete Composites. 2019. No. 103. Pp. 213–223.
15. Li, K., Li, L. Crack-altered durability properties and performance of structural concretes. Cement and Concrete Research. 2019. 124(105811) [Online]. URL: https://doi.org/10.1016/j.cemconres.2019.105811 (date of application: 18.05.2020).
16. Kirthika, S.K., Singh, S.K. Durability studies on recycled fine aggregate concrete. Construction and Building Materials. 2020. 250(118850) [Online]. URL: https://doi.org/10.1016/j.conbuildmat.2020.118850 (date of application: 18.05.2020).
17. Hameed, M.A.S., Maula, B.H., Bahnam, Q.M. An empirical relationship between compressive strength and ultrasonic pulse velocity for concrete. International Review of Civil Engineering. 2019. No. 10 (6) [Online]. URL:https://doi.org/10.15866/irece.v10i6.17061 (date of application: 18.05.2020).
18. Alexander, M., Beushausen, H. Durability, service life prediction, and modelling for reinforced concrete structures – review and critique. Cement and Concrete Research. 2019. No. 122. Pp. 17–29.
19. Geiker, M.R., Michel, A., Stang, H., Lepech, M.D. Limit states for sustainable reinforced concrete structures. Cement and Concrete Research. 2019. No. 122. Pp. 189–195.
20. Khalaf, M.A., Ban, C.C., Ramli, M. The constituents, properties and application of heavyweight concrete: A review. Construction and Building Materials. 2019. No. 215. Pp. 73–89.
21. Sediek, O.A., Wu, T.-Y., McCormick, J., El-Tawil, S. Collapse behavior of hollow structural section columns under combined axial and lateral loading. Journal of Structural Engineering. 2020. No. 6 [Online]. URL: https://doi.org/10.1061/(ASCE)ST.1943-541X.0002637 (date of application: 18.05.2020).
22. Trapko, T. Effect of eccentric compression loading on the strains of FRCM confined concrete columns. Construction and Building Materials. 2014. No. 61. Pp. 97–105.

23. Lu, W.-Y., Chu, C.-H. Tests of high-strength concrete deep beams. Magazine of Concrete Research. 2019. No. 71 (4). Pp. 184–194.
24. Shuyskiy, A.I., Stel'makh, S.A., Shcherban', E.M., Kholodnyak, M.G. Investigation of the influence of the initial composition of heavy concrete designed for the manufacture of ring-section products on its properties. Materials Science Forum. 2018. No. 931, Pp. 508–514. DOI: 10.4028/www.scientific.net/msf.931.508
25. Stel'makh, S.A., Shcherban', E.M., Kholodnyak, M.G. Analysis of concrete deformation diagram, received by different ways of formation, and their separate layers. IOP Conf. Ser.: Mater. Sci. Eng. 2019. 687 (022008) [Online]. URL: https://iopscience.iop.org/article/10.1088/1757-899X/687/2/022008 (date of application: 18.05.2020).
26. Mailyan, L.R., Stel’makh, S.A., Shcherban’, E.M., Kholodnyak, M.G. Determination and use of hidden strength reserves of centrifuged reinforced constructions by means of calculation and experimental methods. Russian Journal of Building Construction and Architecture. 2020. No. 1 (45). Pp. 6–14. DOI: 10.25987/VSTU.2020.45.1.001
27. Stel'makh, S.A., Shcherban, E.M., Zholobova, O.A. Prescription and Technological Aspects of Manufacturing High-Quality Centrifuged Products and Structures from Heavy Concrete. IOP Conf. Ser.: Mater. Sci. Eng. 463 (022056) [Online]. URL: http://iopscience.iop.org/article/10.1088/1757-899X/463/2/022056 (date of application: 18.05.2020).
28. Stel’makh, S.A., Shcherban’, E.M., Shuyskiy, A.I., Nazhuev, M.P. Theoretical and Practical Aspects of the Formation of the Variational Structure of Centrifuged Products from Heavy Concrete. Materials Science Forum. No. 931. Pp. 502–507. DOI: 10.4028/www.scientific.net/msf.931.502

Contacts:

Levon Mailyan, lrm@aaanet.ru
Sergei Stel'makh, sergej.stelmax@mail.ru
Evgenii Shcherban', au-geen@mail.ru