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EXPERIMENTAL RESEARCH ON ASSESSMENT OF CONCRETE'S COMPRESSIVE STRENGTH OF CENTRIFUGAL CONCRETE PILES

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Abstract

Centrifugal concrete products are manufactured using specific technology that changes the concrete proportion during consolidation. The bleeding of water reduces the water-to-cement ratio and increases the compressive strength of concrete. This affects the strength of the concrete determined on conventional casted cylinders, centrifuged hollow cylinders, and drilled cores from piles. This research determines the experimental conversion factor of 80 MPa concrete between casted cylinders and centrifuged hollow cylinders, which is 0.86. The factor between casted cylinders or centrifuged hollow cylinders and drilled cores (diameter of 57 mm and height of 57 mm) is 0.87 or 1.01, respectively. These coefficients can be used in production quality control. Practical verification of established factors was carried out on high-strength prestressed centrifugal piles. It shows that the experimental conversion factor gives more reliable and precise results in converting the strength of drilled cores than the factor recommended in actual national standards. Consequently, larger-scale research is needed to review the national standards or to compile guidelines for centrifugal concrete piles.

Keywords: compressive strength; centrifugal concrete; cylinder specimen; hollow cylinder specimen; drilled core specimen; conversion factor.

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1. Introduction

Centrifugal technology has been widely applied worldwide for manufacturing precast reinforced concrete products since the early 20th century. Almost all products with circular cross-sections, such as poles, columns, and piles, are manufactured using this technology. According to this technology, the centrifugal force created during the rotation of the form at high speed evenly distributes and compactes the concrete mixture along the circumference. At the same time, a part of the mixing water is removed from the mixture and bleeds inside the pile. Thanks to that, the actual water-to-cement ratio of the centrifugal concrete will decrease compared to the water-to-cement ratio of the original concrete mixture. Thereby, the strength of the concrete in centrifugal products is significantly increased. However, because of this, there is a change in the concrete composition, especially the volume of cement paste and the water-to-cement ratio in the cross-sectional thickness of the product. Therefore, the properties of centrifugal concrete are not uniform and differ from the standard vibration-cast samples [1–3].

Research and practical applications have shown that the bearing capacity of centrifugal products depends on the actual strength of the concrete, which is significantly different from the strength of the vibration-cast specimen. The centrifugal regime and the distribution of longitudinal and transverse reinforcement also affect the bearing capacity of the centrifugal products [2, 4, 5]. Research on

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centrifugal piles with a diameter of 1250 mm and a wall thickness of 120 mm using C30 centrifugal concrete [6] shows that the strength of the outer part of the centrifugal pile is greater than the strength of the inner part and is greater than the strength of the vibration-cast specimen. The conversion factor of the compressive strength of the inner part for the one-stage centrifugal regime is 0.85, and for the two-stage regime is 1.25. Meanwhile, this factor for the outer part of both centrifugal regimes equals 1.50.

Research on B40 centrifugal concrete [6] shows that the bulk density of the concrete in the inner part is about 8% lower than that in the outer part, the compressive strength is about 34% lower, and the water content of the concrete mixture after centrifugal forming is 43% higher. Research on centrifugal concrete with a design strength of 50 MPa [7] shows that the compressive strength and bulk density of the drilled cores from the centrifugal concrete pile gradually increase from the inner part to the outer along the pile cross-section. Meanwhile, the correlation between bulk density and compressive strength of cores drilled parallel to the pile axis is not established. The failure characteristics of the cores drilled perpendicular to and parallel to the axis of the centrifugal pile are different. The average strength of cores drilled perpendicular to the pile axis is greater than that of drilled samples parallel to the pile axis.

Concerning B60 high-strength centrifugal concrete, research [8] on centrifugal piles shows that the compressive strength of the outer part can be up to 15% higher than the compressive strength of the inner part of the pile cross-section. Meanwhile, the compressive strength of the middle part has a value close to the strength of the concrete when not divided by part. The variation of the compressive strength depends on many technological factors, in which the concrete strength and the centrifugal regime are essential.

The above analysis shows that due to the specific technology, the actual strength of concrete on centrifugal concrete products is significantly variable and much different from the strength of the vibration-cast specimen. To determine the compressive strength close to the strength of the centrifugal product, Japanese standard JIS A5373:2016 [9] stipulates that the strength test specimen must comply with JIS A 1136:2018 [10], that is, using a hollow cylinder specimen formed by centrifugation and cured according to the same regime as the products. However, TCVN 7888:2014 [11] currently stipulates using 150 mm diameter and 300 mm high cylinder specimens cast and cured according to TCVN 3105:2022 [12] to control the compressive strength. TCVN 7888:2014 [11] also allows the use of hollow cylinder specimens according to JIS A1136 [10] but does not specify the conversion factor. Besides, this standard does not specify the assessment method for drilled specimens taken from piles.

Nowadays, in Vietnam, the strength of concrete on precast structures can be determined using drilled core specimens as stipulated in TCVN 12252:2020 [13]. Accordingly, the compressive strength of the drilled core needs to be multiplied by the β factor to convert to specimens with a H/D ratio equal to 1.0, and the η_1 factor to convert the strength on cylindrical specimens with different diameters and different strengths to the strength of 150 mm cube specimens. The η_1 factor has a tabulated value depending on the converted strength. For the converted strength below 55 MPa, the η_1 factor is specified for each level of 10 MPa value, but for converted strength over 55 MPa, the η_1 factor does not change. The compressive strength of the drilled core of high-strength centrifugal piles determined according to TCVN 12252:2020 [13] may not be accurate and needs to be reevaluated.

It is clear that with the same centrifugal regime and concrete proportion, there will be a certain correlation between the concrete compressive strength determined on the hollow cylinder specimen, the vibration-cast specimen, and the drilled cores. This correlation can be determined experimentally for each specific case and used in production control. This study aims to establish the experimental conversion factor between concrete strength determined on vibration-cast, centrifuged, and drilled core specimens. We also assess the suitability of the production control requirement and calculation procedures for compressive strength of drilled core according to current national standards and the need for revision.

2. Materials and methods

This study was conducted on 02 concrete proportions using raw materials from the VGSI Pile factory with a target compressive strength of 80 MPa. Nghi Son PC50 cement has a normal consistency of 29% and compressive strength at 28 days of 54.1 MPa. Aggregates include crushed granite stone D_{max} = 20 mm, river sand, and manufactured sand with a fineness modulus of 2.4 and 3.1, respectively. Active mineral admixtures are Hoa Phat S95 ground granulated blast furnace slag (C80S proportion) or silica fume (C80M proportion). High-range water-reducing admixture is polycarboxylate based. The properties of the cement, ground granulated blast furnace slag, and silica fume are presented in Table 1, Table 2, and Table 3, respectively. The proportion of the concrete mixture is selected according to the factory's technology and shown in Table 4.

Table 1. Properties of PC50 Nghi Son Cement

Properties	Unit	Value
Specific gravity	g/cm^3	3.16
Volume stability	mm	1.0
Fineness: - Retained on 0.09 mm sieve	%	1.1
- Blaine	cm^2/g	3.790
Standard consistency	%	29.0
Setting time: - Initial	Min.	165
- Final	Min.	210
Flexural strength: - at 7 days	MPa	7.2
- at 28 days	MPa	10.2
Compressive strength: - at 7 days	MPa	34.4
- at 28 days	MPa	54.1

Table 2. Properties of Hoa Phat S95 ground granulated blast furnace slag

Properties	Unit	Value
Specific gravity	g/cm^3	2.91
Moisture content	%	0.35
Activity index: - at 7 days	%	83
- at 28 days	%	102
SO_3 content	%	0.17
MgO content	%	4.96
Cl^- content	%	0.025
Loss on ignition	%	1.46

Table 3. Properties of silica fume

Properties	Unit	Value
Specific gravity	g/cm^3	2.20
Bulk density	kg/m^3	250
Mean particle size	µm	0.15
Strength activity index	%	112.5

Table 4. Concrete proportions

Materials	Content, kg/m^3 for	
	C80S	C80M
Cement	425	436
GGBFS	225	-
Silica fume	-	21.8
Crushed stone	1137	1125
River sand	495	500
Manufactured sand	465	470
Chemical admixture	4.1	5.6
Water	105	108

The concrete mixture is mixed at the factory's batching plant according to the predetermined proportions. After mixing, the concrete mixture is transported to the centrifugal forming area and sampled. The concrete mixture sample is used to cast D150H300 mm cylinder specimens according to TCVN 3105:2022 [12] and D200H300 hollow cylinder specimens (Fig. 1) according to JIS A1136 [10]. We assigned the centrifugal forming regime for hollow cylinders according to the factory's recommendation, which corresponds to the forming regime for 300 mm diameter piles. A set of specimens consists of 3 cylinders and 3 hollow cylinders. Concrete mixture samples were taken from 6 different batches of each proportion. The concrete specimens and piles are cured in a curing chamber (Fig. 2) according to the factory's curing regime at a maximum temperature of 80 °C. After curing, the specimens and the section of the test pipes are transported to the LAS-XD 03 laboratory for capping or coring to make cored specimens for compressive strength tests. Fig. 3 presents the test program.

Figure 1. Hollow cylinder specimen and centrifugal forming test equipment

Figure 2. Curing chamber

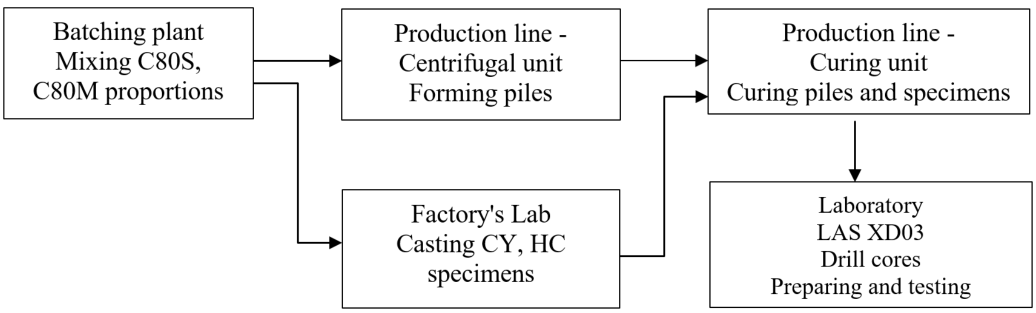

Figure 3. Test program

Assessment of the compressive strength of concrete was also performed on piles produced with the same concrete mixtures on the factory's technological line. The piles have an outer diameter of 300 mm with a wall thickness of 60 mm. The centrifugal forming and curing regimes are performed according to the factory's technological process. With piles and D150H300 cylinder specimens, the appropriate drill bit diameter was selected to obtain a drilled core with a diameter of 57 mm. The drilled core specimens were cut and capped to have a height equal to the diameter. For each concrete mix proportion, 2 piles were produced on 2 different days. Four sets of 3 drilled core specimens were taken in each pile.

The compressive strength of the test specimens was determined at 28 days of age according to TCVN 3118:2022 [14]. In processing the test results of the drilled core specimen, the compressive strength of the specimen was calculated as the ratio of the maximum load to bearing area without applying any correction factor. The strength conversion factor between different samples was selected according to Appendix B of TCVN 3118:2022 [14]. The identification, shape, dimensions, and forming regime of the test specimens are presented in Table 5.

Table 5. Identification and characteristics of the test specimens

Identification	Concrete		Specimens	
	Mixtures	Forming regime	Type	Shape and dimensions
C80S.CY	C80S	vibration	CY (vibration-cast)	cylinder D150H300
C80S.CH	C80S	centrifugal	CH (centrifugal)	hollow cylinder D200H300
C80S.CC	C80S	vibration	CC (drilled from CY)	cylinder D57H57
C80S.CP	C80S	centrifugal	CP (drilled from pile)	cylinder D57H57
C80M.CY	C80M	vibration	CY (vibration-cast)	cylinder D150H300
C80M.CH	C80M	centrifugal	CH (centrifugal)	hollow cylinder D200H300
C80M.CC	C80M	vibration	CC (drilled from CY)	cylinder D57H57
C80M.CP	C80M	centrifugal	CP (drilled from pile)	cylinder D57H57

3. Results and Discussion

3.1. Determination of Experimental Conversion Factor

According to the experimental plan, the compressive strength of the cast and drilled specimens at 28 days was determined. Evaluation of the within-set variation of the strength showed that the coefficient of variation ranged from 0.4% to 2.8%, with an average value of 1.7% for the vibration-cast cylinder specimen and 2.1% for the hollow cylinder specimen. These coefficients of variation were all less than 5%, indicating that the making, curing, and testing of the specimens were properly carried out. The strength of the set was calculated as the average of the strengths of the 3 specimens in the set and is presented in Table 6.

Table 6. Compressive strength of concrete at 28 days

No	Concrete mixtures	Compressive strength (MPa) determined on		
		CY	HC	CC
1	C80S	70.2	89.5	91.6
2	C80S	75.5	92.0	95.6
3	C80S	79.5	94.7	87.3
4	C80S	75.2	87.9	93.4
5	C80S	78.1	93.3	92.8
6	C80S	75.7	94.5	88.7
7	C80M	77.2	84.4	91.7
8	C80M	74.9	91.0	95.8
9	C80M	76.1	89.3	90.9
10	C80M	88.5	93.0	89.5
11	C80M	87.1	81.9	84.3
12	C80M	83.5	89.1	92.6

The data in Table 7 show that the concrete production quality is fairly stable. The coefficient of variation varies between 3.0% and 7.3%, depending on the specimen type and the concrete proportion. The C80M concrete mixture has a slightly higher coefficient of variation than C80S, possibly because when using compressed silica fume, breaking and dispersing fine admixture particles through the batch is more difficult than using ground granulated blast furnace slag with larger and uncompressed

Table 7. The statistical parameters of the concrete mixtures

Parameter	Value for		
	CY	HC	CC
C80S Concrete			
Mean, MPa	75.7	91.6	92.0
Standard deviation, MPa	3.19	3.08	2.77
Variation, %	4.2	3.4	3.0
C80M Concrete			
Mean, MPa	81.2	90.8	88.1
Standard deviation, MPa	5.92	3.82	4.17
Variation, %	7.3	4.2	4.7
C80S and C80M Concretes			
Mean, MPa	78.5	91.2	90.1
Standard deviation, MPa	5.37	3.34	3.93
Variation, %	6.8	3.7	4.4

particles. Concerning the specimen type, the coefficient of variation determined on the hollow cylinder specimen has the lowest value and is less than 5%.

The data from Table 6 show that the compressive strength determined on the hollow cylinder HC, with an average value of 91.2 MPa, is greater than that on the CY cylinder, with an average value of 78.5 MPa. The reason is that the bleeding water during centrifugal forming decreases the water-to-cement ratio of the concrete [1, 5]. The HC specimen formed by a centrifuge in the laboratory has a lower water-to-cement ratio than the CY sample formed on a vibrating plate. This phenomenon also occurs during the pile manufacturing process, so it can be assumed that the strength determined on the HC sample will have a value closer to the centrifuged concrete strength.

The results in Table 6 were also used to determine the compressive strength conversion factor for specimen type. The calculated results are presented in Table 8.

Table 8. Experimental conversion factor

Parameter	Conversion factor for		
	CY/HC	CY/CC	HC/CC
C80S Concrete			
Mean	0.83	0.82	1.00
Standard deviation	0.050	0.029	0.056
Variation, %	6.0	3.6	5.6
C80M Concrete			
Mean	0.90	0.92	1.03
Standard deviation	0.096	0.085	0.043
Variation, %	10.8	9.2	4.1

Parameter	Conversion factor for		
	CY/HC	CY/CC	HC/CC
C80S and C80M Concretes			
Mean	0.86	0.87	1.01
Standard deviation	0.081	0.079	0.051
Variation, %	9.4	9.1	5.0

The results in Table 8 show the difference between the conversion factor determined for the C80S and C80M mixtures. This difference, ranging from 0.03 to 0.10, is not statistically significant and depends on the concrete proportion and the testing process. The combined conversion factor for both mixtures has intermediate values with a coefficient of variation ranging from 5.0% to 9.4%, which meets the requirements of TCVN 3118:2022 [14] (less than 15%). For factory productions where the quality of raw materials and the production process are well controlled, the quality is supposed to be stable, and the conversion factor will not vary much. Russian standard GOST 10180:2012 [15] allows applying the conversion factor and re-checking this factor experimentally after no more than 2 years or after replacing or repairing equipment or molds.

3.2. Determination of on-pile concrete compressive strength

We use the conversion factor in Table 8 to convert the strength of drilled core specimens from factory-produced piles. Test piles are selected and drilled according to section 2. The results of strength determination according to different procedures are presented in Table 9.

Table 9. Compressive strength of the drilled core specimen

Drilled core specimen			Compressive strength (MPa) of				
			Drilled core[1]	Conversion according to TCVN		Conversion according to Table 4[4]	
Pile	Set	Concrete		cube[2]	cylinder[3]	CY	HC
1	S1.1	C80S	75.0	62.3	51.9	65.3	75.8
1	S1.2	C80S	86.5	71.8	59.8	75.3	87.4
1	S1.3	C80S	85.2	70.7	58.9	74.1	86.1
1	S1.4	C80S	90.5	75.1	62.6	78.7	91.4
	Mean value		84.3	70.0	58.3	73.3	85.5
2	S2.1	C80S	77.5	64.3	53.6	67.4	78.3
2	S2.2	C80S	84.8	70.4	58.7	73.8	85.6
2	S2.3	C80S	91.1	75.6	63.0	79.3	92.0
2	S2.4	C80S	93.2	77.4	64.5	81.1	94.1
	Mean value		86.7	71.9	59.9	75.4	87.5
3	M1.1	C80M	78.4	65.1	54.2	68.2	79.2
3	M1.2	C80M	87.2	72.4	60.3	75.9	88.1
3	M1.3	C80M	91.4	75.9	63.2	79.5	92.3
3	M1.4	C80M	93.6	77.7	64.7	81.4	94.5
	Mean value		87.7	72.7	60.6	76.3	88.5

Drilled core specimen			Compressive strength (MPa) of				
			Drilled core[1]	Conversion according to TCVN		Conversion according to Table 4[4]	
Pile	Set	Concrete		cube[2]	cylinder[3]	CY	HC
4	M2.1	C80M	75.8	62.9	52.4	65.9	76.6
4	M2.2	C80M	85.0	70.6	58.8	74.0	85.9
4	M2.3	C80M	84.6	70.2	58.5	73.6	85.4
4	M2.4	C80M	89.1	74.0	61.6	77.5	90.0
Mean value			83.6	69.4	57.8	72.8	84.5

[1] Determined as the ratio of the maximum load to bearing area.
[2] Converted to cube according to TCVN 12252:2020 [13].
[3] Converted from [2] to cylinder D150H300 according to TCVN 3118:2022 [14] using the factor of 1.20.
[4] Conversion factor for CY and HC equals 0.87 and 1.01, respectively.

The results in Table 9 show that the between-set coefficient of variation of the drilled core specimen from centrifugal concrete piles ranges from 6.7% to 8.2%. This variation depends on the production technology, the uniformity of the concrete mixture, and the centrifugal forming regime of the pile. These values show the stability of the quality of the concrete in piles in comparison with manufacturing practices in the region [16].

Determining the compressive strength of drilled core specimens of piles according to TCVN 12252:2020 [13] includes the conversion of the compressive strength of the drilled specimen to the strength of the standard cube specimen (column 5, Table 9) and conversion of the standard cube specimen to D150H300 cylinder specimen with the factor of 1.20 (column 6, Table 9). As a result, we have the converted strength of the cylinder specimen.

The results in Table 9 show that the concrete strength has been significantly reduced when converted according to the TCVN 12252:2020 [13]. The standard converted cylinder strength is about 0.69 times the drilled core specimen strength. This strength value is much lower than the compressive strength of the concrete mixture used for producing centrifugal piles. Meanwhile, as shown in the introduction, the centrifugal forming reduces the water content and increases the concrete strength. Thus, this conversion method is not appropriate. According to this conversion procedure, for the converted compressive strength to reach 80 MPa, the strength of the drilled core specimen should be more than 115 MPa. This is because, for concrete with compressive strength of more than 55 MPa, TCVN 12252:2020 [13] specifies the coefficient $\eta_1 = 0.83$. For concrete with strengths from 35 MPa to 45 MPa and from 45 MPa to 55 MPa, this coefficient has the corresponding values of 0.97 and 0.92. The coefficient η_1 is as referred to GOST 28570-90 [17]. However, the 2019 updated version of GOST 28570-90 [17] has changed the regulations on the coefficient η_1. Therefore, it is necessary to review the value of this coefficient based on the local experimental data. In addition, to convert the compressive strength from the standard cube specimen to the cylindrical specimen, TCVN 3118:2022 [14] specifies the conversion factor as equal to 1.20. Several studies [18–21] have shown that the value of the shape-size conversion factor for high-strength concrete is smaller than that of normal-strength concrete and less than 1.20. Thus, this conversion factor for high-strength centrifugal concrete should be reviewed.

We also apply the experimental conversion factor in Table 8 to convert the compressive strength of drilled core specimens to the strength of standard cylinder specimens (Table 9, column 7) and hollow cylinder specimens (Table 9, column 8). The converted compressive strength is closer to the strength of cast specimens in the laboratory (Table 6). The results showed that the converted compressive strength of cylinder specimens was lower than that of hollow cylinder specimens. The compressive strength converted to hollow cylinder specimens for 04 piles varies from 84.5 MPa to 85.5 MPa, while the value converted to cylinder specimens varies from 72.8 MPa to 76.3 MPa. Thus, it is possible that with the same compressive strength of the drilled core specimens, the concrete is considered not satisfied if converted to the strength of the cylinder specimens but satisfied if converted to the strength of the hollow cylinder specimens. As shown above, the vibration-cast cylinder specimens have a higher water-to-cement ratio than the centrifugal specimens, meaning they do not correspond to the water-to-cement ratio of centrifugal-forming concrete. Therefore, hollow cylinder specimens should be used for quality control, and TCVN 7888:2014 should be revised. Cylindrical cylinders can also be used for in-plant control if the input material and processing conditions are kept constant and the appropriate correlation is established.

The above experimental results and analysis show some problems in applying current national standards TCVN 7888:2014 [11] and TCVN 12252:2020 [13] in the determination, quality control, and assessment of the concrete compressive strength of centrifugal piles. It also shows that larger-scale studies are needed to review the standards or compile specific guides on the determination and assessment of the concrete strength of centrifugal concrete piles.

4. Conclusions

Based on the research result, we can come to the following conclusions:

Centrifugal forming of concrete products changes the proportion and water-to-cement ratio of concrete. This needs to be taken into account in the determination and assessment of compressive strength. The compressive strength determined on the hollow cylinder specimens is more suitable for centrifugal technology than the vibration cast specimens.

The experimental conversion factor from the cylinder to the hollow cylinder specimens for 80 MPa centrifugal concrete of 0.86 was established. The conversion factor from the D57H57 drilled core specimen to the cylinder and the hollow cylinder specimens were 0.87 and 1.01, respectively. These factors can be used in the quality control of production.

Converting the compressive strength of drilled core specimens to standard specimens following the national standards produces a much lower value than that with the experimental conversion factor and strength of vibration-casted specimens. In addition, the compressive strength of centrifugal hollow cylinder specimens is more suitable for the quality control of centrifugal concrete.

It also shows that larger-scale studies are needed to review the standards or compile specific guidelines on the determination and assessment of the concrete strength of centrifugal concrete piles.

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