7. Komanduri, R., Brown, R. H. (1981). On the Mechanics of Chip Segmentation In Machining. Journal of Engineering for Industry, 103 (1), 33–51. doi: https://doi.org/10.1115/1.3184458
8. Shaw, M. C., Vyas, A. (1993). Chip Formation in the Machining of Hardened Steel. CIRP Annals – Manufacturing Technology, 42 (1), 29–33. doi: https://doi.org/10.1016/s0007-8506(07)62385-3
9. Thamizhmanii, S., Sulaiman, H. (2012). Machinability Study Using Chip Thickness Ratio on Difficult to Cut Metals by CBN Cutting Tool. Key Engineering Materials, 504-506, 1317–1322. doi: https://doi.org/10.4028/www.scientific.net/kem.504-506.1317
10. Dogra, M., Sharma, V. S., Dureja, J. (2011). Effect of tool geometry variation on finish turning – A Review. Journal of Engineering Science and Technology Review, 4 (1), 1–13. doi: https://doi.org/10.25103/jestr.041.01
11. Das, S. R., Panda, A., Dhupal, D. (2017). Experimental investigation of surface roughness, flank wear, chip morphology and cost estimation during machining of hardened AISI 4340 steel with coated carbide insert. Mechanics of Advanced Materials and Modern Processes, 3 (1). doi: https://doi.org/10.1186/s40759-017-0025-1
12. Campocasso, S., Poulachon, G., Costes, J.-P., Bissey-Breton, S. (2014). An innovative experimental study of corner radius effect on cutting forces. CIRP Annals, 63 (1), 121–124. doi: https://doi.org/10.1016/j.cirp.2014.03.076
13. Sumardiyanto, D., Susilowati, S. E., Cahyo, A. (2018). Effect of Cutting Parameter on Surface Roughness Carbon Steel S45C. Journal of Mechanical Engineering and Automation, 8 (1), 1–6.

UDC 666.982.2.033:666.973.4
DOI: 10.15587/1729-4061.2019.174491

EFFICIENCY ANALYSIS OF THE TECHNOLOGY OF ROLLER FORMATION OF FINELY-GRAINED CONCRETE PRODUCTS

O. Lazarieva
Doctor of Economic Sciences, Associate Professor*
S. Belinska
PhD, Assosiate Professor**
E-mail: melek2405@bigmir.net
P. Lavrinev
PhD, Assosiate Professor*
N. Rudenko
PhD**
*Department of Land Management***
**Department of Accounting and Audit
***Petro Mohyla Black Sea National University
68 Desantnykiv str., 10, Mykolaiv, Ukraine, 54003

Викладена ефективність використання технології роликового формування примусового повороту робочого органу (ролика чи сектора). Представлені результати розробки удосконаленої технології роликового формування. Особливостями цієї технології є відсутність прослизання і заклинювання робочого органу відносно поверхні бетонної суміші, що формується. Воно виникає за рахунок зростання інерційних сил роликів, що вільно обертаються.

Вказані переваги даної технології перед вібраційною, а саме:

– можливість суміщення в одному агрегаті процесів розкладання, ущільнення та загладжування бетонної суміші, що створює, в першу чергу, можливість організації високомеханізованих та автоматизованих технологічних ліній, і, тим самим, підвищити їх продуктивність:

– можливість ефективного ущільнення особливо жорстких дрібнозернистих бетонних сумішей, що, в свою чергу, створює передумови для отримання довговічних виробів, скорочення циклів термообробки, а також зменшення металомісткості виробництва;

– можливість використання дрібнозернистих сумішей з нестачею цементного тіста, що не перевищують норми для бетону на крупному заповнювачі;

– можливість ефективного покращення санітарно-гігієнічних умов для обслуговуючого персоналу за рахунок відсутності вібрації і суттєвого зниження шуму;

– відмова від дороговартісного і у ряді випадків дефіцитного крупного заповнювача, що дозволяє отримати значну економію.

Зазначені залежності характеризують і показують збільшення пресуючого тиску робочого органу на поверхню виробу, що формується. В результаті цього коефіцієнт ущільнення суміші збільшується з 0,983 (при вільному оберті ролику) до 0,998 (при примусовому його оберті)

Ключові слова: дрібнозерниста суміш стабілізуюча балка, фібробетон, сталефібробетон, стальні волокна, орієнтація фібри, примусовий оберт сектора

Received date 22.01.2019
Accepted date 15.07.2019
Published date 12.08.2019

1. Introduction

The need to increase efficiency of capital construction is inextricably linked with improvement of the reinforced concrete technology. Development of new and improvement of existing concrete forming methods substantially determine product quality and cost which is of great importance. Prospective and relevant forming methods include the non-vibrational method of roller formation which in comparison with the widespread vibration method ensures:

– compaction of very hard concrete mixtures including fine concrete mixtures which makes it possible to save cement and fillers being scarce in some regions, increase durability and strength of products;

– improvement of working conditions, increase in work productivity due to a higher level of process mechanization (and the possibility of process automation), increase in reliability of equipment due to the absence of vibration, reduction of noise;

– reduction of energy consumption for heat treatment and specific quantity of metal in mould inventory.

The technology of non-vibrational roller formation of fine-concrete products opens up new promising opportunities for improving quality of the products formed by forced (slippage-free) rotation of the working body (sector or roller). In addition, the possibility of extending the scope of its application through development of a technology for forming steel-fiber reinforced concrete is also relevant and promising taking into account the high strength characteristics of fine concrete.

2. Literature review and problem statement

The technology of non-vibrational roller forming of fine concrete products was comprehensively studied and described in [1]. At the same time, this source does not adequately cover and substantiate possibilities of efficient compaction of very hard fine concrete mixtures. Consequently, prerequisites for obtaining durable products, reducing the cycle of heat treatment as well as reducing the specific quantity of metal in production of concrete products can be created [2].

It is fair to think [3] that the technology of non-vibrational roller forming has prospects of application in production practice. Namely there, determination of loads in elements is important. However, the study does not take into account the fact that fine concrete and steel-fiber reinforced concrete of roller forming have higher physical and mechanical characteristics.

The use of vibrational technologies is limited by the concrete mixture hardness which relates to cement content. It is believed that the use of non-vibrational roller forming technology can significantly improve hardness of concrete mixture, improve working conditions and create conditions for process automation [4]. Concerning solution of the problem of advanced technologies of roller forming, it is noted in [5] that it is worth to point out the technology of using cement compositions with high initial strength. That is why attention is concentrated on the innovative approach to development of fine concrete grades. The approach is based on nanotechnologies based on controlling the structure of hydrate phases and the hydration processes to create a cementing matrix with improved properties [6]. It is considered that one of the ways to production of fine concrete consists in the use of cement compositions having high initial strength. Provision of a necessary chemical and mineralogical composition by introducing special additives into the raw material is the main way to obtaining such cementing components [7]. It is believed that when the roll forming process is used, steel fibers acquire a planar orientation in the concrete matrix which contributes to improvement of strength characteristics of steel-fiber reinforced concrete.

The most essential results of studies in the roller forming technology concerning determination of the process productivity, forces acting on the working bodies and strength of main drives are presented in [8]. Results were obtained with roller forming equipment with an account of position of the working body (roller) relative surface of the concrete mixture being formed. The process of forming very hard steel-fiber reinforced concrete mixtures using the roller forming technology may proceed with slippage which is the main problem there. At the same time, free rotation of the compacting roller may cause jamming relative to the surface of the formed mixture caused by the growth of inertial forces of the freely rotating roller. Slippage reduces the force of friction between the roller and the mixture surface and, hence, pressure on the mixture which in turn entails reduction of the degree of mixture compaction, especially near the mould walls. Moreover, the roller may further rotate by inertia in a direction opposite to the direction of movement of the stabilizing beam without seizure of the mixture and interaction between it and the surface of the compacted mixture.

Paper [9] presents the results obtained in the study of physical and mechanical properties of concrete and steel-fiber reinforced concrete products (floor grating for livestock farms, posts for grape espaliers, curb stones, etc.) manufactured by the same roller technology with free roller rotation. Because of the low pressure of the roller on the formed concrete mixture and low coefficient of compaction (K_{comp}=0.89–0.92), durability of the products was 120–150 cycles of alternating freezing and defrosting. Besides, a device was proposed in [10] in which free rotation of rollers was replaced by forced rotation. It was believed that the products manufactured by the studied technology of high-tech concrete rapidly harden and have multi-level structure due to systemic combination of nano- and ultra-dispersed mineral components and super-plasticizing additives [11]. Influence of the blade design of gravitational concrete mixers on quality of the prepared building mixtures was studied in [12]. In this context, use of the motion mode of a roller forming unit with a cam driving gear providing reciprocating motion of the forming trolley [13] was substantiated.

Analysis of published sources on the technology of non-vibrational roller formation of fine concrete products has shown that this method is the most effective for compaction of very hard fine concrete mixtures. Constructive comprehension of this problem allows us to conclude that the results of the above scientific studies did not have a noticeable effect on the process of analysis of efficiency of the roller forming technology of fine concrete products.

This relates to the fact that theoretical groundwork needs adaptation to the conditions under which technologies will be used. However, conditions greatly differ and it is impossible to take into account variety of their specifics.

That is why the need of solution of the problems of forming fine concrete products has put on the agenda development of a new technology of roller forming fine concrete products with forced rotation of the working body.

3. The aim and objectives of the study

This study objective was to develop a technology for the manufacture of products and structures of fine concrete and steel-fiber reinforced concrete by roller forming with forced rotation of the working body. This will enable the following:

– compaction of very hard concrete mixtures including fine and steel-fiber reinforced concrete mixtures which would make it possible to save cement and coarse filler materials that are scarce in some regions;

– increase in strength and durability of products;

– improved working conditions, higher work productivity due to a higher level of process mechanization, noise reduction and rise of equipment reliability due to absence of vibration;

– reduction of energy consumption for heat treatment and specific quantity of metal in the mould inventories.

To achieve this objective, the following tasks were set:

– derive regression equations that can be used in calculating process schedules of roller forming of fine concrete with forced rotation of the working body taking into account the achieved qualitative characteristics of products, productivity of equipment, forces acting on this equipment and mould moving forces;

– derive a regression equation of the process schedules of roller forming steel-fiber reinforced concrete mixtures;

– achieve an increase of not less than 20 % in strength characteristics of fine and steel-fiber reinforced concrete produced with the use of roller forming with forced rotation of the working body compared to the free roller rotation technology;

– achieve a 15–20 % reduction of portland cement consumption in production of fine concrete using roller forming with forced rotation of the working body.

4. Study of a new technology of roller forming fine concrete and steel-fiber reinforced concrete products

4. 1. The essence of the advanced method of roller forming with forced rotation of the working body

This method essence lies in the fact that the mixture is compacted by pressing its new portions continuously coming from the service bunker into lower layers. The forming process starts in a fixed position of the mould until a mixture ridge is formed at the non-filled side of the mould. Presence of this ridge indicates achievement of the limit compaction of the mixture under the forming sector. Then the drive of continuous mould moving is switched on until the mould enters from the opposite side of the unit. In this case, the mould speed is a technological factor which in a combination with other equipment parameters provides certain degree of concrete compaction (Fig. 1).

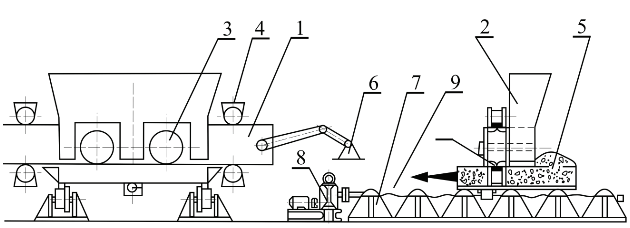

Fig. 1. Structural diagram of the roller forming devices: 1 – beam; 2 – service bunker; 3 – forming rollers; 4 – guides; 5 – mould; 6 – crank mechanism; 7 – roller table; 8 – mould drive; 9 – drive screw

The following data were taken for the experiments: the sector radius R_c=210 mm, the sector length l_c=300 mm, the number of double movements of the beam per minute n=40–70; the beam width B_b=300 mm, thickness of the formed products: h_{prod}=50–250 mm.

Brand 400 portland cement was used as a binder with consumption from 330 to 650 kg/m^3. In this case, the following composition of mixtures was used: a composition with full filling of hollow spaces in sand with cement slurry, mixtures with separation of sand grains and mixtures with scarce cement slurry. Fibers of low-carbon steel of general purpose with strength of 600 MPa were used as fibers for dispersion reinforcement of concrete, The fiber dimensions taken: length l=25–50 mm, diameter d=0.5 mm. Percentage reinforcement of steel-fiber reinforced concrete varied from 0.8 to 1.6 vol. %.

4. 2. Study and development of roller forming process schedules

Forming very hard fine concrete mixtures by roller technology with free roller rotation which can lead to slippage and jamming relative to the mixture surface is continuation of studies [8, 9]. This phenomenon is caused by growth of inertial forces of rotating rollers.

Presence of slippage reduces the force of friction between the rollers and the mixture surface and leads to a decrease in thickness of the mixture layer and, accordingly, decrease in pressure on the mixture which in turn results in a smaller degree of mixture compaction, especially at the mould walls. Moreover, the rollers even may rotate in a direction opposite to the direction of motion of the stabilizing beam, that is, without seizure of the mixture to be compacted and creation of pressure forces between the roller and the mixture surface.

It has been found that forced turn of the sector approximates the degree of concrete compaction to 1 in contrast to free rotation of rollers at identical forming conditions (Fig. 2).

A diagram of influence of forming conditions on the degree of compaction of the concrete mixture (two series of experiments were conducted) is shown in Fig. 2. Curves 1, 2 and 3 (series 1) were constructed based on the results obtained on the test stand with free rotation of rollers. Curves 4, 5 and 6 (series 2) were constructed based on the experimental data obtained on the same stand but with forced turning of the sector.

Analysis of the curves shows that in the process of mixture compaction with the use of the roller technology, both with free roller rotation (curves 1, 2 and 3) and with forced turning of the sector (curves 4, 5, 6) relative to the mixture surface, the degree of concrete compaction tends to the limit according to formula (1). Thus, we can conclude that formula (1) is fair for both free and forced rotation of the working body when concrete mixtures are compacted with the use of the roller technology.

The diagram in Fig. 2 clearly shows that forced turn of the sector significantly increases degree of compaction of the concrete mixture in comparison with free roller rotation. For example, maximum compaction factor was 0.983 at a free roller rotation and 0.998 at a forced turn of the sector in the same forming conditions.

The more detailed analysis of the curves shows that in experiments with free roller rotation, the mixtures with scarce cement slurry in the intergranular space were better compacted than the mixtures with complete filling of hollow spaces with cement slurry and the mixtures with excess cement slurry. This is explained by the fact that it is easier for the forming machine to compact mixtures having specially reserved hollow spaces in sand for cement slurry. To compact the mixtures where there is no such reserve of hollow spaces, the machine has to spend extra energy to provide dense compaction of the mixture components. In experiments with forced turning of the sector, this pattern is less pronounced (experiment series 2, curves 4, 5 and 6). This phenomenon is explained as follows. Forced turning of the sector in the stand of roller formation significantly increases maximum contact pressure (up to 0.78–0.84 MPa instead of 0.45 MPa at free roller rotation) between the sector and the concrete mixture surface which in turn significantly increases intensity of compaction which reduces the effect of the concrete mixture composition on the compaction degree.

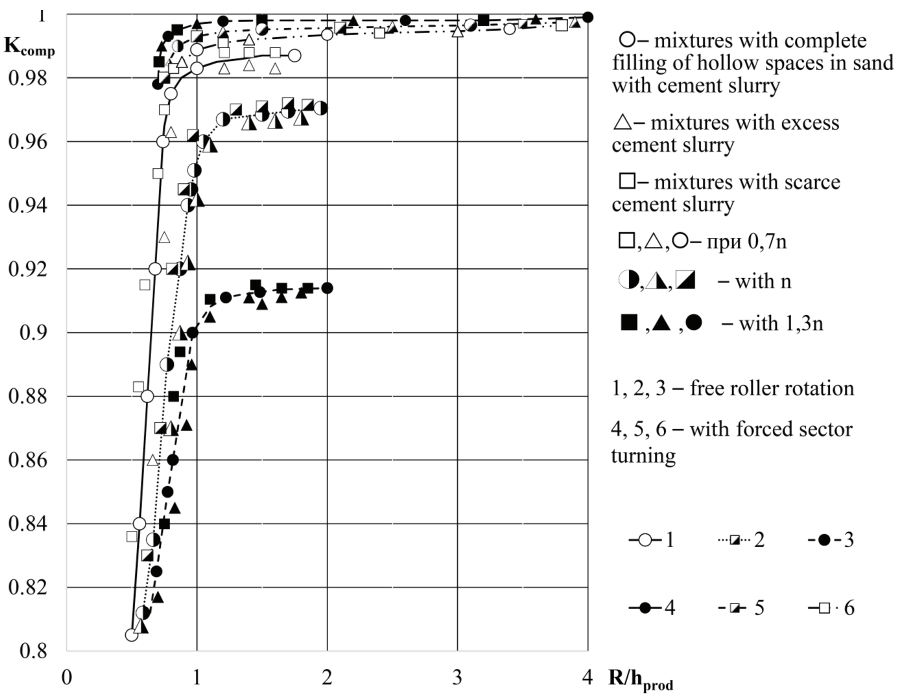

Fig. 2. The graph of influence of forming conditions on the degree of compaction of concrete mixture

It is also clear from the graph in Fig. 2 that in experiments with free roller rotation there was a sharp decrease in the degree of mixture compaction with an increase in frequency *n* of the working body impact on the concrete mixture (the curves 2 and 3 lie below the curve 1). Such a pattern was not found in the experiments. On the contrary, with an increase in impact frequency, the coefficient of compaction slightly increased (the curves 4 and 5 lie above the curve 6). This change in the coefficient of compaction is explained by the fact that when forming by the roller technology with free roller rotation, there was slippage of the roller relative to the compacted mixture surface because of growth of inertial forces with the growth of frequency *n* and corresponding reduction of traction forces. Besides that, as experiments have shown, there was no such slippage in the case of forced turning of the sector.

It was established in [8] that when there is free rotation of rollers, the highest degree of mixture compaction is achieved if the following condition is satisfied:

$$H_{prod}=(0{,}9{:}1)R, \tag{1}$$

where R is the radius of the compaction roller; H_{prod} is the largest degree of concrete compaction.

Expression (1) is true for the up to 150 mm high products. It was experimentally established that if height of the product being formed exceeds 150 mm, then radius R of its lower part will be 10–15 % smaller.

Physical and mechanical properties of fine concrete of roller forming have been studied when assessing its quality. These include off-axis compression strength, extension at bending, frost resistance, degree of abrasion, water absorption, degree, and homogeneity of compaction of freshly formed concrete.

For conducting experimental studies, fine concrete mixtures with cement content from 330 to 650 kg/m^3 were used. Concrete mixtures with water to cement ratio from 0.276 to 0.545 were prepared in rotor-type concrete mixers of enforcement action. Duration of the composition mixing was 1.5–3 min. Physical and mechanical properties of concrete were determined on the following specimens: cubes with 70 mm rib dimension and 70×70×280 mm prisms cut from slab fragments after a 20-day solidification in normal temperature and moisture content conditions.

4. 3. Determining mathematical dependences of strength characteristics of fine concrete and steel-fiber reinforced concrete

To construct a mathematical model of strength characteristics of fine concrete, the method of mathematical experiment planning was used. To obtain more reliable dependences, two three-factor linear plans were adopted: one for the mixtures with scarce cement slurry in the intergranular plane of compacted sand and the other for the mixtures with excess cement slurry.

At the same time, both plans covered the area with full filling of hollow intergranular spaces in the compacted sand with cement slurry. Factors varied within the following values: X_1 (cement content, kg/m^3) from 330 to 490, X_2 (W/C, water to cement ratio) from 0.285 to 0.545, X_3 (thickness of the product, mm) from 70 to 230 for mixtures with scarce cement slurry and X_1=490–650 kg/m^3; X_2=0.277–0.307; X_3=70–230 mm for mixtures with excess cement slurry.

Processing and analysis of changes in strength characteristics of concrete have allowed us to obtain linear regression equations depending on the factors under study, namely:

a) for mixtures with scarce cement slurry (2) to (5):

$$R_C^B = 43.96 + 12.46X_1 - 2.59X_2 - 3X_3, \tag{2}$$

$$R_C^H = 41.3 + 12.06X_1 - 2.19X_2 - 5.64X_3, \tag{3}$$

$$R_{PH}^B = 4.88 + 1.2X_1 - 0.23X_2 - 0.27X_3, \tag{4}$$

$$R_{PH}^H = 4.88 + 1.149X_1 - 0.69X_2 - 0.67X_3; \tag{5}$$

b) for mixtures with excess cement slurry (6) to (9):

$$R_C^B = 65.44 + 13.75X_1 - 2.16X_2 - 4.09X_3, \tag{6}$$

$$R_C^H = 61.79 + 12.14X_1 - 2.21X_2 - 7.74X_3, \tag{7}$$

$$R_{PH}^{B} = 6.66 + 0.96X_1 - 0.46X_2 - 0.34X_3, \quad (8)$$

$$R_{PH}^{H} = 6.26 + 0.81X_1 - 0.75X_2 - 0.74X_3, \quad (9)$$

where R_C^B, R_{PH}^B are compression strength and tensile strength in the upper layer of the product subjected to bending, MPa; R_C^B and R_{PH}^H are compression strength and tensile strength in the lower layer of the product subjected to bending, MPa.

In addition, experiments have been conducted on concrete friction resistance. They have shown that friction resistance depends on:

– cement content (friction varied from 0.25 to 0.5 g/cm^2 with cement content from 330 to 650 kg/m^3 at W/C=0.28);

– on the water to cement ratio (friction varied from 0.32 to 0.48 g/cm^2 at cement content of 490 kg/m^3 and W/C=0.28–0.4);

– on thickness of the product being formed (friction varied from 0.25 to 0.63 g/cm^2 at H_{prod}=70 to 250 mm). The degree of abrasion of the samples prepared on the vibration table and tested in laboratory was 2.5 times higher than that of roller formed concrete specimens.

$$K_{cmpr} = 4.9\times10^{-1} - R_0\left(2.7 + 0.26\times P\right)\times10^{-3} + 4.2\times10^{-2}\times P, \ \frac{\text{g}}{\text{cm}^2}, \quad (10)$$

where R_0 is strength at K_{cmpr}=1 at full filling of hollow spaces, MPa; P is concrete porosity, percent.

It is known that the higher the strength of concrete before hydrothermal treatment, the less structure violations will be in concrete during warming-up and, accordingly, the harder thermal treatment conditions can be used. The study results have shown that intensity of strengthening of the freshly roller formed concrete with forced sector turning was considerably higher than that of the roller formed concrete with free roller rotation, a fortiori, of the vibration formed concrete. For example, strength of the roller formed concrete with forced turning of the sector ranged from 0.6 to 0.8 MPa a half an hour after forming while strength of the concrete compacted by freely rotating rollers was 0.4 to 0.5 MPa. Strength was an order of magnitude lower in vibration compacted concrete, even two hours after forming.

In order to determine the possibility of forming steel-fiber reinforced concrete mixtures with the use of roller technology with simultaneous studying strength characteristics of steel-fiber reinforced concrete and influence of fiber reinforcement on strength characteristics of concrete (Table 1).

When steel fibers were added to the concrete mixture (Table 1) in an amount of 1.6 vol. %, compression strength was on average 135 % relative to the concrete matrix and was equal to 80–88 MPa. Tensile strength in bending was on average 240–243 % relative to the concrete matrix and was equal to 15–16 MPa and tensile strength in splitting was on average 220 % relative to the concrete matrix and was equal to 5–7 MPa. It was found that such increase in strength is typical for mixtures with both W/C=0.26 and W/C=0.32.

A two-factor linear plan was used to construct mathematical models of strength characteristics of steel-fiber reinforced concrete. At the same time, the varying factors fluctuated within: X_1 (water to cement ratio) from 0.26 to 0.32, X_2 (fiber content in vol./% of the concrete mixture) from 0.8 to 1.6.

Table 1

Averaged data on influence of volume content of fiber reinforcement (l=50 mm, d=0.5 mm) on strength characteristics of steel-fiber reinforced concrete (cut along the slab)

Composition, kg/m^3				Strength, MPa		
Cement	Sand	Water	Fiber, %	R_{avg}	R_f	R_s
500	1,750	160	1.6	80.9/136	14.8/243	5.3/221
500	1,750	130	1.6	88.3/135	16.3/240	7.0/219
500	1,750	160	0.8	70.4/115	9.8/160	3.7/141
500	1,750	130	0.8	75.0/114	11.1/163	4.5/140
500	1,750	145	1.2	79.3/126	12.8/203	5.3/182
500	1,750	145	1.2	78.5/125	12.5/198	5.2/180
500	1,750	145	1.2	77.8/124	12.2/195	5.1/779
500	1,750	130	–	65.6	6.8	3.2
500	1,750	145	–	62.8	6.3	2.9
500	1,750	160	–	59.6	6.1	2.6
Vibratory forming						
590	1,700	236	–	33	3.4	–
590	1,700	236	05	36/109	5.0/150	–
590	1,700	236	1.0	39/118	6.5/191	–
590	1,700	236	1.5	41/124	8.3/244	–
590	1,700	236	2.0	45/136	9.9/291	–

Processing and analysis of these results of measurement of strength characteristics of steel-fiber reinforced concrete have allowed us to obtain linear regression equations and their changes depending on the factors under study, namely (10) to (12):

$$R_C^{\Phi} = 78.65 - 3X_1 + 5.85X_2, \quad (10)$$

$$R_{PH}^{\Phi} = 13 - 0.71X_1 + 2.55X_2, \quad (11)$$

$$R_{PP}^{\Phi} = 5.25 - 0.5X_1 + 1.15X_2. \quad (12)$$

Steel fibers during compression of a steel-fiber reinforced concrete mixture by of roller forming were oriented in the matrix in the direction of force action. For example, tensile strength in bending of the prisms cut along the slab was 25 to 30 % higher than the strength of the prisms cut across the slab (Table 2).

Table 2

Results of testing prism specimens of steel-fiber reinforced concrete for tensile strength in bending depending on their cutting direction, MPa

Cutting across the slab	N	R_{avg}	Cutting along the slab	n	R_{avg}
10.5	25		14.6	62	
11.6	28	11.0	15.1	76	14.8
10.9	31		14.7	68	
7.1	14		9.7	23	
7.8	16	7.5	9.7	24	
7.6	14		10	29	9.8
9.4	18		13.1	47	
9.6	22	9.6	12.6	38	12.8
9.5	19		12,7	43	

Note: n is the amount of fiber reinforcement in the section of the beam fracture

Initially, fibers of 50 mm in length were used in the experiments. Tensile tests in compression of prism specimens have shown that fracture was accompanied by a characteristic crackle. As it was established by thorough inspection, this crackle appeared during fracture of prisms as a result of fiber breakage. The presence of this breakage shows that the force binding the fibers with the cement stone exceeds breaking strength of the fiber itself.

Steel-fiber reinforced concrete formed by rolling is highly resistant to erosion. For example, the average degree of friction was 0.19 g/cm^2 at 0.8 % reinforcement and 0.11 g/cm^2 at 1.6 % reinforcement (Table 3).

Table 3

Averaged data on the influence of volume content of fiber reinforcement (l=50 mm, d=0.5 mm) on strength characteristics of steel-fiber reinforced concrete (specimen cut along the slab)

Experiment No.	Slab No.	Composition, kg/m^3 Strength, MPa						
		Cement	Sand	Water	Fiber, %	R_c	R_f	R_s
1	1	500	1,750	160	1.6	80.9* / 136	14.8 / 243	5.8 / 221
2	2	500	1,750	130	1.6	88.3 / 135	16.3 / 240	6.0 / 219
3	3	500	1,750	160	0.8	70.4 / 115	9.8 / 160	3.7 / 141
14	4	500	1,750	130	0.8	75.0 / 114	11.1 / 163	4.5 / 140
15	5	500	1,750	145	1.2	79.3 / 126	12.8 / 203	5.3 / 182
16	6	500	1,750	145	1.2	78.5 / 125	12.5 / 198	5.2 / 180
17	7	500	1,750	145	1.2	77.8 / 124	12.2 / 195	5.1 / 179
53	8	500	1,750	130	–	65.6 / 100	6.8 / 100	3.3 / 100
54	9	500	1,750	145	–	62.8 / 100	6.3 / 100	2.9 / 100
55	10	500	1,750	160	–	59.6 / 100	6.1 / 100	2.6 / 100

*Note: * in MPa above the line, in % to fine concrete under the line*

This is 4.2 times higher than the degree of abrasion of steel-fiber reinforced concrete compacted by vibration.

This formula was derived from analysis of numerous experimental studies:

$$C_f = K_{cmpr} - 0.125M,\ \frac{g}{cm^2}, \tag{13}$$

where K_{cmpr} is the degree of abrasion of the concrete matrix determined from formula (10); M is volume percentage of reinforcement of the concrete matrix.

Steel-fiber reinforced concrete of roller forming has a lower degree of water absorption (2.5–3 wt. %).

The foregoing suggests application of the roller technology with forced rotation of the working body to the production of concrete and steel-fiber reinforced concrete products, namely: floor grating for cattle-breeding farms, poles for grape espaliers, tram-line slabs, multilayer decking, manhole slabs for drain shafts, curbstones, fence panels and loggia screens, airfield slabs, sidewalk slabs, multi-hollow slabs, etc.

4. 4. Establishment of interconnections in the technology of roller forming of fine concrete products and steel-fiber reinforced concrete products

Recommendations on the manufacture of reinforced concrete products by the roller forming method make it possible to develop a more advanced technology and roller forming equipment as well as manufacture the structures of steel-fiber reinforced concrete taking into account physical and mechanical characteristics of the material.

The relatively narrow area of application of the roller forming technology is explained by the fact that during the process of forming the concrete slabs reinforced with spatial frames, cracks occur because of deformation of the reinforcing frame. Therefore, one of the promising areas of application of this roller forming technology which may demonstrate its significant advantages are the products with dispersed steel-fiber reinforcement.

Studies on determining the parameters of forming concrete and steel-fiber reinforced products were carried out in conditions of industrial production with forced turning of the sector.

5. Determination of the process performance, magnitude of the pressures acting on the mould elements and the mould traction forces in the roll forming process

As a result of data processing, dependences were obtained that take into account the forced turning of the sector and allow to determine the following:

a) productivity of the forming process (14):

$$Q = 9{,}84 \times 10^{-3} \times P \times R_s (1 - \cos\lambda_1) \times \times l_c \times b_{prod} \times n \times K_1,\ \frac{m^3}{c}, \tag{14}$$

where Q is the process productivity, m^3/s; P is porosity of freshly formed concrete, %; R_s is the sector radius, m; l_c is the sector length, m; n is the number of double strokes of the beam per minute; b_{prod} is the product width, m; K_1 is the coefficient characterizing influence of percentage of fiber reinforcement M on the mixture consumption as determined by the graph in Fig. 3.

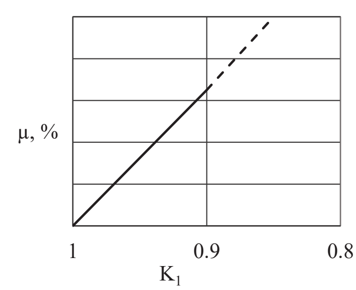

Fig. 3. Dependence of the volume percent of fiber reinforcement μ on coefficient K_1

λ is the angle of bite of the sector axis determined from the formula (15):

$$\lambda_1 = (0.189 + 0.0573\,W/C) \times \times \left(0.829 + 4.53 \times 10^{-3} \times n\right),\ \text{rad}, \tag{15}$$

b) maximum pressures acting on the bottom (P_{max}) and the sides (P_s) of mould (16):

$$P_{max}=\frac{K_T\times K_2}{K_0}\times R_C\left(1-\cos\lambda_1\right)\times 10^2,\ \text{MPa},\qquad(16)$$

where K_T is the technological coefficient equal to: 1 for the products formed without partitions and reinforcement; 1.7 for the products formed in moulds with partitions; K_2 is the coefficient characterizing influence of the percentage of fiber reinforcement, M, on the resistance magnitude and is determined from the graph in Fig. 4.

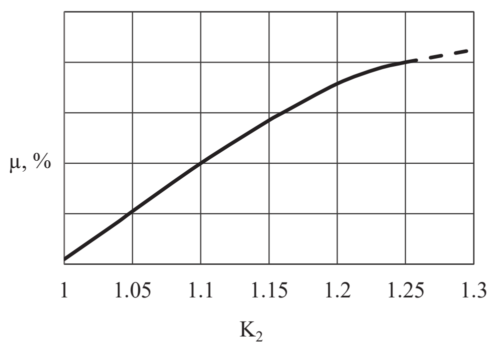

Fig. 4. Dependence of volume percentage of fiber reinforcement on K_2

K_c is the coefficient depending on the frequency of action of the compaction sector on the concrete mixture determined from formulas (17) to (19):

$$K_c=6\times 10^{-2}\times n-0.8\ ,\ \frac{\text{C}^2\times\text{M}^2}{\text{kg}},\qquad(17)$$

$$P_s=K_s\times P_{max}=$$

$$=\frac{K_s\times K_m\times K_2}{K_C}\times R_C\left(1-\cos\lambda_1\right)\times 10^2,\ \text{MPa},\qquad(18)$$

where K_s is the coefficient of side influence equal to 0.7.

$$N=\frac{K_m+K_3}{K_c}\times R_c\left(1-\cos\lambda_1\right)\times R_{KB}\times$$

$$\times W\left(\begin{array}{l}K_n\times L_c\times a\sqrt{\dfrac{R_c\times V_f\times S}{l_c\times b_{ns}\times n}}\times 10^3+\\+B_s\times b_{prod}\times 10^5\end{array}\right),\ \text{kW},\qquad(19)$$

where K_3 is the coefficient characterizing influence of percentage of fiber reinforcement M on the magnitude of capacity. It is determined from the graph in Fig. 5.

R_{cr} is the radius of the drive crank, m; a is the number of sectors; V_f is the mould speed, m/s; S is the the area of section of the product being formed across the mould movement direction, m^2; W is the angular speed of the crank, s^{-1}; B_w is the width of the stabilizing beam; K_n is the coefficient of rolling-over resistance determined from formula (20):

$$K_n=6.11\times 10^{-2}\times n+0.37,\qquad(20)$$

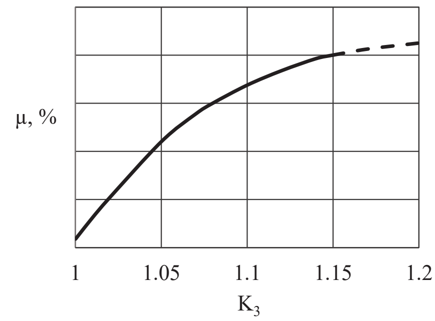

Fig. 5. Dependence of volumetric reinforcement on K_3

c) traction force required for moving the mould (21):

$$F_f=0.85\times 10^6\times\frac{K_T+K_4}{K_c}\times R_c\left(1-\cos\lambda_1\right)\times$$

$$\times\left[l_c\times a\sqrt{\frac{R_c\times V_f\times S}{l_c\times b_{ns}\times n}}\times 10^4+0.25B_s\times b_{prod}\right]\times K_{CK},\ \text{N},\qquad(21)$$

where K_4 is the coefficient characterizing influence of percentage of fiber reinforcement, M, on the value of traction force and is determined from the graph in Fig. 6.

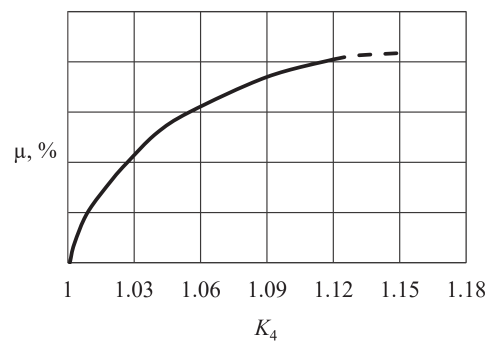

Fig. 6. Dependence of K_4 on the volume percentage of fiber reinforcement

K_s is the coefficient of metal-metal slip equal to 0.2.

6. Determining economic efficiency of the technology of roller forming with forced rotation of the working body

Economic efficiency of application of the technology of roller forming with forced rotation of the working body was experimentally studied at the Zorya-Mashproekt Research and Production Complex of Gas Turbine Engineering (Mykolaiv, Ukraine).

Introduction of this technology in the production of products of fine concrete and steel-fiber reinforced fine concrete will make it possible to reduce cement consumption and increase service life of products of this concrete.

Economic effect due to reduction of cement consumption by 50 kg per 1 m^3 of the product at a price of 61.2 conv. unit/t will be (22):

$$E_f=61.2\times 0.05=3.06\ \text{conv.units.}\qquad(22)$$

At a planned output volume of 3,000 m^3/year, annual economic effect will equal (23):

$$E_{f1} = 3.06 \times 3000 = 9180 \text{ conv.units.} \quad (23)$$

Economic effect due to increased frost resistance of the products with a 1.4 times higher service life expectancy (24) to (27) will be:

$$E_{f2} = A(C_1 - C_2), \quad (24)$$

where A is the annual production, C_1 is the curbstone production cost before implementation, 14.99 conv. units; C_2 is the adjusted curbstone production cost after implementation (25):

$$C_2 = C_2 ai \times \frac{T_1}{T_2}, \quad (25)$$

where C_2 *ai* is the estimated curbstone production cost after implementation: 12.25 conv. un.; T_{bi} is the curbstone service life before implementation; T_{ai} is the curbstone service life after implementation;

$$C_2 = 12.25 \times \frac{12}{18} = 8.21 \text{ conv.units,} \quad (26)$$

$$E_{f2} = 3000(12.25 - 8.21) = $$
$$= 3000 \times 4.04 = 14200 \text{ conv.units.} \quad (27)$$

The overall economic effect is (28):

$$E_{ov} = E_{f1} + E_{f2} = 9180 + 14200 = 21300 \text{ conv.units.} \quad (28)$$

This research work was carried out using fine concrete (quartz sand was used as a filler). When using coarse aggregate (gravel), hollow spaces may occur in the process of concrete mixture compaction as a result of gravel jamming. The conducted rapid experiments have shown that coarse aggregate can be added to a concrete mixture in a volume not exceeding 20 % of the total mixture volume.

In this case, it is necessary to additionally specify size of the coarse aggregate fraction.

7. Discussion of results obtained in the study of the roller forming technology with forced rotation of the working body

The results obtained are explained by the following factors:

– application of forced rotation of the working body of the roller forming equipment instead of free rotation relative to the compacted surface of the concrete mixture;

– thickness of the product being formed should be no more than the radius of the working body (roller or sector);

– steel fibers are oriented in the matrix in the direction of the acting forces when steel-fiber reinforced concrete mixture is compacted by roller forming. Due to this, tensile strength in bending of the prism specimen cut along the plate was 25 to 30 % higher than the strength of the prism cut across the slab.

The main feature of the proposed roller forming technology and the obtained products of concrete and steel-fiber reinforced concrete with high physical and mechanical qualities consists in the use of forced rotation of the working body (roller or sector). Free rotation of the working body results in its slipping and jamming on the surface of the mixture being formed because of increasing forces acting on the freely rotating rollers. Occurrence of slippage reduces friction between the roller and the surface of the mixture which results in a decrease in degree of the mixture compaction.

The following requirements and limitations are inherent in this study:

– thickness of the product being formed should be no more than the radius of the working body (roller or sector);

– volume of a coarse aggregate in the concrete mixture should be no more than 20 % of the total volume of the product. Otherwise, hollow spaces not filled with cement-sand mixture are formed in the process of forming;

– fraction size of a coarse aggregate should be no more than 10 to 20 mm;

– proportion of steel fibers in the steel-fiber reinforced concrete mixture should be no more than 1.6 vol. %. Otherwise, clots of steel fibers are formed in the process of forming.

One of limitations of this study consists in the small width of the products being formed, namely, 80 to 100 cm. However, in the long run, this disadvantage can be eliminated by installing two or three working bodies (rollers or sectors) on the stabilizing beam.

The further development of this study may include the following:

– forming products from concrete of various types with various heavy and light fillers;

– forming fiber reinforced concrete depending on the used fibers (steel wire, glass fiber) and their length and diameter;

– selecting strength of the main drive of the roller forming unit depending on the type and size of the products, their material, hardness of the concrete mixture and other factors.

In the process of development of this study of the roller forming technology, difficulties of experimental nature may occur. Taking into account the fact that the technology is rather new and inadequately studied, there is a need for a large number of experimental laboratory studies prior to its industrial implementation. In doing so, it is necessary to take into account the type and size of products, their composition, filler characteristics, fiber characteristics, hardness of the formed mixture, loads acting on the mould sides and bottom and other factors.

8. Conclusions

1. Roller forming technology is one of the most progressive technologies in the production of concrete, reinforced concrete and steel-fiber reinforced concrete products from very hard fine concrete mixtures. It has been proved that forced rotation of the working body (sector or roller) increases efficiency of the equipment and improves quality of the products being formed.

2. It was established on the basis of the conducted studies that:

– the greatest degree of concrete compaction both in free and forced rotation of the working body is achieved provided that the working body radius be equal to the height of the product being formed;

– forced rotation of the working body prevents formation of structural defects in the form of shifts in the newly formed concrete and increases uniformity of concrete compaction;

– forced turn of the sector increases the degree of compaction of concrete in comparison with the option of free rotation of rollers from 0.902 to 0.997;

– this technology makes it possible to effectively use fine concrete in the production of concrete and steel-fiber reinforced concrete products without coarse aggregates.

The obtained results make it possible to conclude that steel fibers take a planar directional orientation in the concrete matrix during roll forming which contributes to the growth of strength characteristics of steel-fiber reinforced concrete.

3. It was established that fine concrete and steel-fiber reinforced concrete of roller forming have higher physical and mechanical qualities, namely:

– fine concrete and steel-fiber reinforced concrete of roller forming have a high abrasion resistance (friction of concrete is from 0.25 to 0.6 g/cm^2 and steel-fiber reinforced concrete has friction from 0.11 to 0.19 g/cm^2 which is 2.3 and 4.2 times lower than that obtained by vibration technology;

– products of concrete and steel-fiber reinforced concrete of roll forming can withstand 300 cycles of alternating freezing and defrosting;

– intensity of strength growth of the fresh formed concrete of roller formation is from 0.6 to 0.8 MPa in half an hour while strength was an order of magnitude lower in concrete compacted by vibration, even in a few hours;

– when steel fibers are added to a concrete mixture in the amount of 1.6 % of the mixture volume, compression strength is on average 135 % of that of the concrete matrix and equals 80 to 88 MPa. Tensile strength in bending is on average 240 to 243 % and is equal to 15–16 MPa and tensile strength at splitting is on average 220 % compared to the matrix and equals 5 to 7 MPa;

– fine concrete and steel-fiber reinforced concrete of roller forming have a relatively low degree of water absorption which indicates their high density (water absorption of concrete varies from 3 to 5 wt. % and that of steel-fiber reinforced concrete and is from 2.5–3 wt. %.

4. As a result of processing the experimental data on forming fine concrete and steel-fiber reinforced concrete, dependences were derived that take into account forced turning of the sector and make it possible to determine:

– productivity of the roll forming process;

– maximum resistance force acting on the bottom and sides of the mould;

– strength of the main drive of roller formation equipment.

We recommend that the obtained results should be used to define more precisely and improve the technology of non-vibrational roller formation of fine concrete products, both at the stages of design and under actual operation conditions.

References

1. Amerikanskaya tekhnika i promyshlennost' (2017). Arhitekturnoe stroitel'stvo. Sbornik reklamnyh materialov. Moscow, 365.
2. Nazin, V. M., Osipov, V. A. (2016). Proizvodstvo zhelezobetonnyh trub v Pol'she. Promyshlennost' stroitel'nyh materialov, 7, 4–7.
3. Korolev, N. E., Ovsyannikov, I. D. (2016). Ustanovka bez vibratsionnogo radial'nogo pressovaniya rolikovoy golovkoy beznapornyh trub. Promyshlennost' stroitel'nyh materialov, 12, 12–15.
4. Kazarin, S. K. (2011). Povyshenie sroka sluzhby rolikovyh golovok truboformovochnyh stankov radial'nogo pressovaniya. Oborudovanie dlya proizvodstva tsementa i sbornogo zhelezobetona, 2, 23–27.
5. Malolepshy, J., Kotwica, L., Konyk, Z., Zak, R. (2014). Rapid-hardening cements with addition of anhydrite-lime sinters. Cement-Wapno-Beton, 1, 40–45.
6. Plank, J. (2015). C-S-H – PCE Nanocomposities for Enhancement of Early Strength of Cement. IBAUSIL 19, 1, 759–766.
7. Sanytsky, M. (2007). Mechanism of alkali-containing complex chemical admixtures and Portland cements interaction. Proceed. 10th Int. Congress on the Chemistry of Cement. Gotenborg, 3, 158–167.
8. Korolev, N. E., Kuzin, V. N., Selivanova, S. A. (1970). Formovanie zhelezobetonnyh izdeliy metodom rolikovogo pressovaniya. Trudy NIIZHB, 22, 32–38.
9. Kuzin, V. M., Selivanova, S. A. (2015). Voprosy kachestva izdeliy rolikovogo formovaniya. VKN: Tekhnologiya bezvibratsionnogo formovaniya zhelezobetonnyh izdeliy. Minsk, 133–139.
10. Sevostianov, I. V. (2014). Ekspluatatsiya ta obsluhovuvannia mashyn. Vinnytsia: VNTU, 88.
11. Rana, A. K., Rana, S. B., Kumari, A., Kiran, V. (2009). Significance of Nanotechnology in Construction Engineering. International Journal of Recent Trends in Engineering, 1 (4), 46–48.
12. Ferraris, C. F. (2001). Concrete mixing methods and concrete mixers: State of the art. Journal of Research of the National Institute of Standards and Technology, 106 (2), 391. doi: https://doi.org/10.6028/jres.106.016
13. Loveikin, V. S., Pochka, K. I. (2016). Dynamichna optymizatsiya kulachkovoho pryvodu mashyn rolykovoho formuvannia. Kyiv: TsP «Komprynt», 176.