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Research Article

Placement of Dry-Mix Shotcrete in Tunnels: Literature Review on Rebound

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Abstract

Shotcrete is widely used in tunnels construction due to its flexibility in placement concrete as underground support, whose rebound material directly affects its quality and cost of projects. In the present work, a review of the state of the art of the last four decades is carried out on the placement factors that influence the rebound of dry-mix shotcrete; where the main parameters that affect it have been identified first, then its behavior is analyzed; next, the relationships and implications related to its process are discussed, giving the necessary explanations for its understanding; then, case studies on simulations of applications in the laboratory and site are included for their quantification; and finally, recommendations and rebound are provided as short or medium term research topics. After this extensive review, it is concluded that the minim rebound percentages for the spraying velocity of 100-114m/s is 25%, for the nozzle distance of 0.5-1.5m is 10%, for a spraying angle of 90o, for the angle of the surface of 0o and 90o is 5-15% and for a layer thickness of 50mm is 30%. Likewise, the two case studies presented reflect the need to carry out simulations in the laboratory and or on site to have a better representation of the real conditions of application in construction projects; On the other hand, the recommendations and future perspectives include conclusions on the study of other parameters associated with dosage and transport, and the need to include nanomaterials, ecological and cementitious materials.

Keywords: Dry-mix shotcrete, Rebound, Nozzle distance, Spraying angle, Angle of the surface

1. Introduction

In the shotcreting of Dry-Mix Shotcrete (DMS), the mixture of cement and dry aggregates (or with a small percentage of moisture, less than 4%) is done in a concrete plant, subsequently, the assembly is transported pneumatically by means of pressurized air through the delivery hose to the nozzle, in which water is added to the mix, depending on the consistency; which guarantees its quality and is subject to the experience of the nozleman and good knowledge of placement techniques; if required as the case, admixtures are included in the dry mix or water. In this shotcreting process, the length of the hose can be significant and the spraying velocity is high.

The rebound (R) directly affects different aspects related to the production of shotcrete such as, among others, the economy of the work, whenever there is loss of material; Also, to the compactness of the placed mix, due to the existence of an excess of pores and air trapped inside and, to the safety and hygiene of the personnel who carry out the projection, due to the impact of the aggregates and the formation of dust in the area being sprayed.

The purpose of this article is to summarize from the existing literature the main parameters related to the placement of DMS, which directly affect on R in tunnels construction.

2. Rebound

In the placement of the DMS, the component materials from their mixing to until reaching support on which it is projected, go through different mixing situations, starting with a starting mix, passing this to a transported mix, then it becomes in a projected mix, to finally get the placed mix.

During the placement process, there is a projected mix that is lost, and that corresponds to the R; than when impacting on the surface, either on the ground or in the air,

which directly affects the quality and cost per m^3 of the Hardened Dry-Mix Shotcrete (HDMS).

This loss is highly variable and depends on different parameters, among which we can mention:Spraying Velocity (SV) [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]; Nozzle Distance (ND) [2], [3], [4], [15], [7], [16], [17], [19], [12], [20], [21], [22], [23], [24], [25]; Spraying Angle (SA) [2], [3], [4], [26], [7], [27], [28], [8], [29], [30], [31], [25], [32], [18], [33], [11], [20], [34], [21], [14], [35], [22], [23], [15], [16], [17], [24], [25], [18], [36]; Angle of the Surface(SA) [1], [2], [37], [6], [27], [38], [25], [11], [34], [13], [39], [14], [35], [40], [17], [24]; Surface Type [1], [2], [37], [6], [25]; Surface Roughness [2], [37], [6], [16], [25]; Surface Moisture [1], [37]; Amount of Reinforcement [41], [27], [16], [17], [42]; Nozzleman [2], [37], [3], [4], [41], [15], [7], [43], [44], [16], [25]; Nozzle Type [19], [25]; [45], [36]; Gunman [1], [40], [16]; Nozzle Mottion [1], [15], [23], [25]; Mechanized Spraying [1], [36]; Air Flow [9], [46], [10], [32], [19], [34], [13], [22], [16], [17], [25], [36]; and Layer Thickness (LT) [1], [2], [3], [4], [6], [26], [16], [47], [29], [25], [11], [19], [13], [14], [22], [16], [17], [25], [36].

In the case of DMS, of the parameters mentioned, the SV, ND, SA, AS and LT will be described, which are the ones with the highest incidence on R.

3. Analysis

A. Spraying Velocity

The mix that is transported by delivery hose must have a constant SV, without intermittent flows, to guarantee a homogeneous continuity of the flow, so that an efficient placement of the projected mix is obtained.

Ref. [38], in Fig. 1 shows the variation of the percentage of R as a function of the VP, showing that the percentage of R is lower for low SV and that, on the contrary, for high SV the R increases, existing minimum values of R of 25% for an optimal value of SV comprised between the range of 100-110 m/s.

On the other hand, [38] in Fig. 2 presents a correlation between SV, compressive strength and percentage of R. In the indicated figure, the author comments that for an optimal SV of 114 m/s there corresponds an R of 8%.

B. Nozzle Distance

An adequate ND between the nozzle and the substrate ensures that the particles have fully penetrated the mix. There are different ranges of values or quantities defined for this ND, which are a function of the placement, being 0.5-1.5m[35], 0.6-1.8m[5], 0.9-1.5m[48], 1.0-2.0m[49]; and the values of 1.2m[9], and 1.5m for [35], who indicates that the ND varies depending on different factors: the type of application and guidanceof spraying (manual, automatic and robot), the limited areas of work, the amount of steel, the danger of rock fall, the adherence to the type of surface, the compactness of the mixture placed and the amount of air; for this case [31] consider a value of 1.4m.

In Fig. 3, taken from [32], shows the distribution of the percentage of R for different values of ND (a), showing that the optimal ND (a) results in an R for 10% and that for variations of a 25% of that ND, the R increases to 25%.

On the other hand, [38] presents in Fig. 4 the influence that the ND and the ASP have on the R. From this we can indicate that for small values of the ND, of the order of 0.75m, an R of the 21%, while, when the ND reaches higher values, up to 1.25m, the percentage of R is 25%. Instead, for a ND value equal to 1.00m, a minimum percentage of R of 10% is achieved, these results are similar to those obtained in [17], [32], [50], [51], [52], [53].

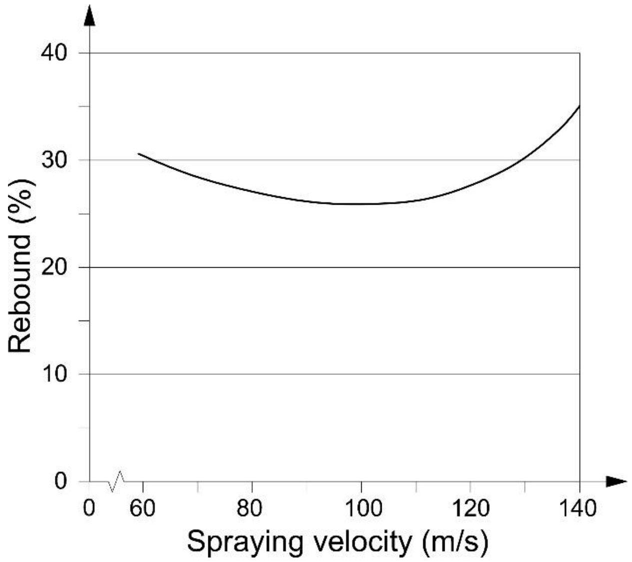

Fig. 1 Variation of rebound as a function of the spraying velocity

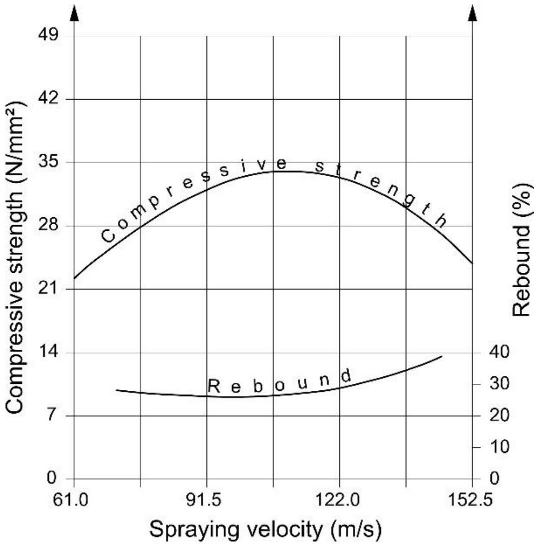

Fig. 2 Influence of spraying velocity on compressive strength and rebound

C. Spraying Angle

The SA is also a very important setting parameter that has a great influence on the R, which reaches its optimum value when the shotcreting is perpendicular to the support. [31] indicates that when going from an angle of 0º (perpendicular to the wall) to an angle of 30º the R increases by 10-15%. Also consider that, for areas with a high density of reinforcement, vertical surfaces adjacent to the ground, unstable areas with rockfalls and corners formed by the intersection of two surfaces, the angle is never less than 45º and the closest to 90º, value equal to that given by [35].

Ref. [37] in Fig. 5 shows us the influence of the SA on the percentage of R where it can be seen that as the SA increases, the percentage of R decreases reaching the value of 13% for an angle of 90º. This value coincides with those indicated by [17], [27], [50], [51], [52], [53], [39].

D. Angle of the Surface

The AS may vary [16], due to the type of applications, including tunnels, reservoirs, pools, canals and those associated with the repair of various structures. In Fig 4 given by [38] and shown previously, it can be seen that the percentage of R grows as the SA varies from 0º (wall position) to 90º (ceiling position), with the minimum and maximum values corresponding to 10- 12% and 20-25%.

In this same direction [32], he obtains the results presented in Fig. 6. In view of them, it can be indicated that the percentage of R is similar to that found by [38]. However, the aforementioned author found a range (5-15%)

of values for the wall position (0º) and a lower range (20-30%) for the ceiling position (90º), these ranges are a little lower than the ranges (5-25%) and (25-50%) for wall and ceiling indicated by [50]. On the other hand [54], it indicates that the rebound percentage varies with the type of aggregates (washed river or crushed stone), finding that for a 10mm crushed stone of it obtains the values of 18%, 14% and 9% for the positions overhead (90º), vertical (0º), and bottom (270º).

E. Layer Thickness

The first moments of a mix shotcretingare those that have the greatest influence on R [34] due to the fact that the surface on which it is projected does not have the minimum amount or has only a few millimeters of material. In Fig. 7 [47] he studies the influence of the LT on the R, determining that the percentage of R decreases as the LT increases, finding that from a 50mm LT the R tends to be constant.

4. Discussion

A. Spraying Velocity

The variation in the rebound percentage is a consequence of the impact of the shotcreting on the surface. Thus, when a concrete mix is placed with a great impact on the surface as a result of the high SV at the outlet, its basic components (aggregates, water and cement), penetrate into the layer of the placed mix without being able to adhere to it by insufficient thickness, so its material that R is produced in large percentages.

However, when there is a low SV at the outlet, that is, it produces less impact on the surface, the coarse aggregates rebound in less quantity while the water and cement do not reach to be placed in the layer of placed mix, contributing all this so that the percentage of R is lower.

Given this situation, is necessary to consider the shotcreting with an optimal SV, which favors that the components of the placed mix have, on the one hand, a greater penetration as the initial layer that receives the concrete is formed and on the other hand, they are completely wrapped, thus contributing to the fact that the R of the largest grains is as low as possible and that minimum R percentages are obtained.

B. Nozzle Distance

The influence of ND is manifested in the sense that there is a dependence, on the one hand, on the compaction and, on the other, on the amount of movement of the projected mix. Thus, in the case of a large ND, the compaction does not develop adequately because the impact of the mix produces an insufficient depth of penetration of the aggregates within the concrete, which is why they rebound, with respect to the amount of movement; its displacement velocity is sufficient at the moment of impact to produce the penetration of the solid components of the concrete in the projected layer, so the R of the mix is lower.

On the other hand, if the ND is small, the projected mix would bounce when hitting the surface because the impact is high and does not favor the incrustation of the aggregates in the projected layer and the mix presents a high R. Regarding the amount of movement, it should be noted that this due to the high speed of impact presents a high percentage of R of the projected mixture. Therefore, it will be necessary to establish an optimal ND that guarantees the appropriate combination of both compaction and amount of movement, thus generating a mix placed with a minimum percentage of R.

C. Spraying Angle

The incidence of SA depends on the orientation of the jet during shotcreting. Thus, when the application is made perpendicular to the surface, the angle of R is smaller and the trajectory of the rebounding particles is almost identical to those of impact. This favors the aggregates to embed themselves in the projected layer and to be adequately enveloped by it, which contributes to a lower R.

Instead, in the case of having an application with an oblique SA to the surface, the path followed by the R angle after impact will be greater, producing a high percentage of R from the thick concrete components.

D. Angle of the Surface

The behavior of the AS on the R is differentiated by gravity. Thus, for a shotcreting directed towards the ground, gravity contributes to the majority of the basic components of the projected mix being placed and, in turn, the material that R is embedded on the surface to which it is projected. In this way, a greater quantity of the projected mix is placed, therefore, the percentage of R will be minimal.

On the other hand, in the case of an shotcreting oriented towards the overhead, gravity prevents the development of a uniform velocity of arrival of the projected mix, decreasing the velocity of the coarse grains and increasing the effect of compressed air in the placement of the fine ones, contributing in this way that the components of the placed mix do not develop a correct adhesion on the surface; therefore, a maximum R percentage occurs.

Now, for a shotcreting directed towards the wall (perpendicular to the surface), what is stated in section III D. is presented, and the percentage of R is the minimum, corresponding mainly to coarse aggregates.

E. Layer Thickness

The variation of the LT is related to the amount of material of the placed mix that exists on the shotcreting surface. Since, at the beginning of the shotcreting, the cement, small aggregates and paste that surround them, do not adhere easily or do so minimally, causing the medium and coarse aggregates to R, this because there is no initial concrete mixture that serves as base.

As we increase the LT, the medium and coarse aggregates become embedded on the existing mix base, and when this layer increases to half the diameter of the coarse aggregate [55], it allows it to penetrate and adhere, which favors the that the percentage of R decreases.

5. Case Studies

Below are some cases where R is quantified, considering the parameters under study, by means of the laboratory simulation of the shotcreting with differents guidance of spraying, robot and manual on test panels.

A. Spraying robot

Rigorous research trials on the influence that ND and SA have on R were developed by [13], [43] for stationary industrial production of DMS production test platform at the University of Bochum in Germany. The sprayingrobot was used with a SV of 25m/s on a vertical surface, for 2 forms of pointing the movement of the nozzle, fixedand circular.

For the ND, a 90º SA of the robot was considered for 5 distance values: 0.5m, 1.0m, 1.5m, 2.0m and 2.5m. The results found indicate that a minimum R percentage is reached for the ND of 1.5m. This value is within the range of 1.0-2.0m found by [17], [39].

In the case of the SA, a ND of 1.5m and 3 SA values of: 0º (equal to 90º), 15º (equal to 75º), 30º (equal to 60º) were taken. The results obtained indicate that the minimum R percentage is achieved with an SA of 90º. This value coincides with those found by [21], [32], [32], [51], [52].

B. Spraying manual

A significant number of underground construction projects have been underway in Canada for several decades. [56], carries out an exhaustive selection of projects with the compilation of typical mixtures designs with steel fibers and silica fume on DMS and wet-process shotcrete, used in tunnels and mines. With this data collection, 2 typical mix designs are developed for each of the projected concretes, in order to carry out different laboratory tests to evaluate the Fresh Dry-Mix Shotcrete (FDMS), the R of the concrete on the surface and the HDMS.

In the case of R, with a sprayingmanual it is quantified in a rebound chamber, the mixture used presents a relationship a/c = 0.3-0.4, the amount of cement varies from 18-21% and the gradation of the aggregates corresponds to type No.1 or No.2. After studying the influence that AS has on R, it is found that with a mix without silica fume and for a overhead position (90º) the percentage of R is 54.6%; Now, for a wall position (0º) the percentage of R is 35%; this result coincides with the maximum value of the range of values of 15-35% given by [34].

6. Final Remarks And Future Perspectives

After the meticulous selection, review and analysis of the extensive and varied technical literature of the last four decades (1980-2220) on the placement factors that influence the R material, we can indicate the following:

There is a large number of parameters that influence the placement of DMS applied to tunnels, the main and most referenced are the SV, ND, SA, AS and LT; which contribute to the formation of a greater quantity of R, which affects the quality and cost of the placed mix.

The results found on the percentages of R, in some cases present marked differences between them, because the conditions of execution of the projects are very varied and the tests that resemble these conditions present certain difficulties related to the parameters associated with the dosage of the initial mix: aggregates, admixtures, additions, cement and water; and to the transported mix: shotcreting machine, nozzles and air compressor.

An obvious difficulty is the very little existence of up-to-date technical literature on the implementation factors that affect the R, which is why it has been necessary to resort to technical documents with some antiquity coming from different contexts: research, industry, project specifications, standard specifications, and diverse geographical areas to have a varied and deep specialized knowledge, which fully illustrates the level of depth required to understand the complex mechanism of R [57], [58]. This difficulty could be due, on the one hand, to the fact that the delivery equipment, nozzleman and rodman used to placement the mix represent a high cost and, on the other, to the need to have a project in execution that coincides with the moment in which the study is planned; Also, it could be due to not having a conditioned work area, either in the laboratory or in the field, that simulates the real work conditions for its application.

The parameters studied must be optimized to achieve the least amount of R, presenting optimal ranges for SV and ND; insted forSA and LT there are optimal values; while for AS the values are obtained according to the position it adopts, being considered higher for a overhead application.

As future research, it is recommended to study the influence of other placement parameters inorder to cover the scarce existing documents and the lack of updated information, that allows knowing their behavior with respect to R, being able to address for example: the air flow supplied by the compressor, the thickness of the FDMS, etc.

Having to supply an optimal air flow favors the aggregates to reach the ideal speed to embed themselves in the surface of the ground, without the reaction of the latter to cause a detachment of the FDMS and consequently the R of the components of the mix placed. In the same way, defining a minimum thickness, by means of the progressive placement of the material, starting from a very fine mix that serves as a support for the initial mortar and that later increases in thickness with the shotcreting of the mix, allows the aggregates to adhere to the start, they are then partially embedded and finally can be fully covered, reaching a thickness of highly compact mix and with a minimum R.

Consider the study of other materials for the composition of the mix, such as: mineral admixture, including fly ash, black carbon and metakaolin, because the size of their particles better controls the mix and reduces the material of the R [59]; also, cementitious materials such as flash metakaolin, blast furnace slags and silica fume can be added, which by influencing the consistency of the mix produce less R [60]. Nanomaterials, such as nanosilice and nanoalumina, can also be studied because they are extremely fine, they fill the pores of the structure of the Calcium Silicate Hydrate (C-S-H) gel, providing an improvement in its microstructure [61], [62], which contributes to a good adherence of the mix on the surface and consequently a lower R. Another types of materials that can be used are ecological ones, obtained through a post recycling manufacturing process of previously used glass bottles, such as glass powder that, due to its fine particles, improves the plasticity of the mixture obtaining a under R [63].

Carry out scale simulation tests in the laboratory or on site tests on test panels or real tests directly on site, so that these are more representative of the specific conditions of their application; For example, in underground constructions, perform R measurements for the different application positions in the cross sections of tunnels and or caverns, thereby obtaining a more exact quantification of the percentage of R, which will directly affect the highest performance during the shotcreting, in the health of the nozzleman, gunman and in the lower cost of the project.

In conclusion, theoretical investigations related to the other implementation parameters mentioned above and not developed in this article, are scarce and their process is poorly understood. Therefore, the R mechanism requires extensive theoretical and experimental investigations, which can be complemented, due to the situations exposed before, with the elaboration on mathematical models, their simulation and then constrasting them under different real situations applied to the construction of tunnels.

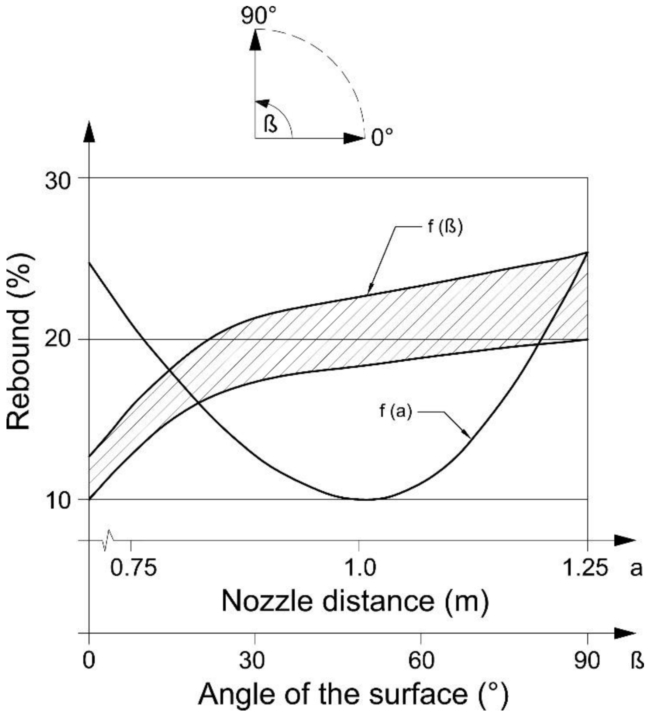

Fig. 4 Rebound in the function of nozzle distance(a) and angle of the surface (β)

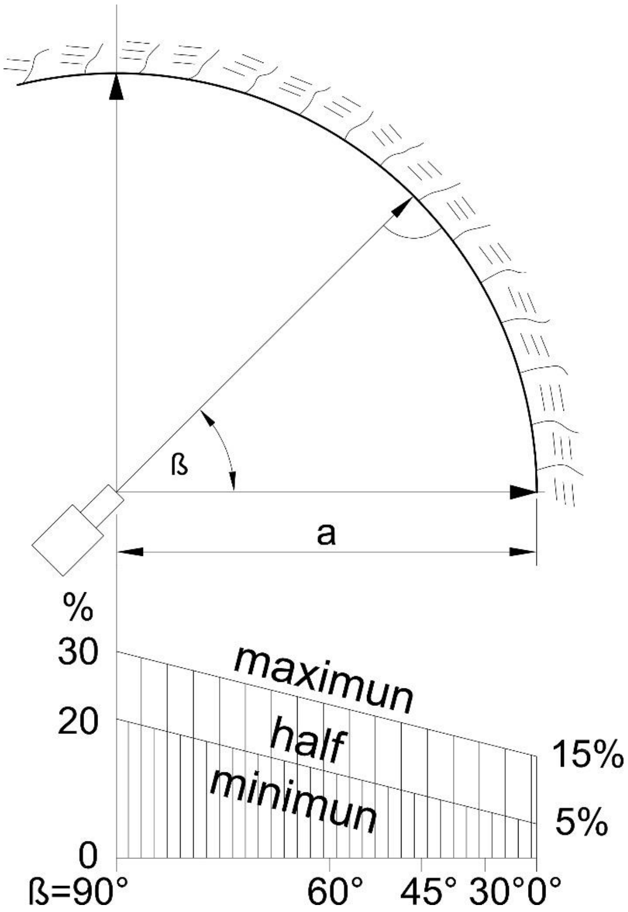

Fig. 6 Rebound value according to the angle of the surface (β)

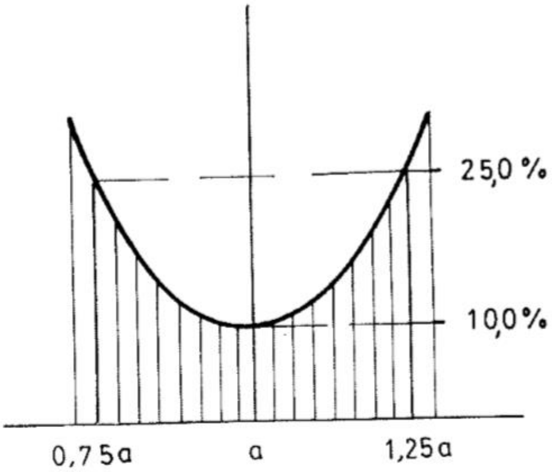

Fig. 3 Rebound value according to nozzle distance (a)

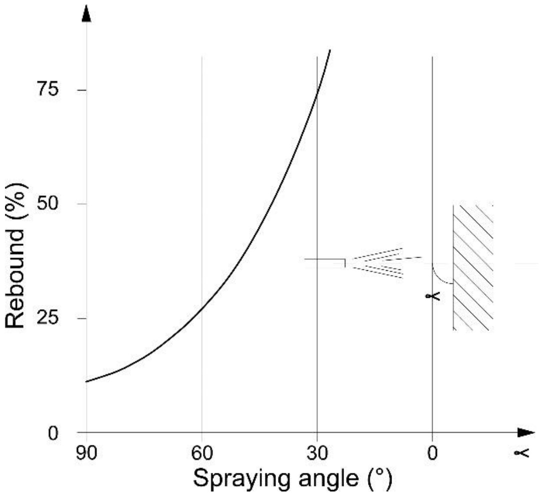

Fig. 5 Influence of spraying angle on rebound

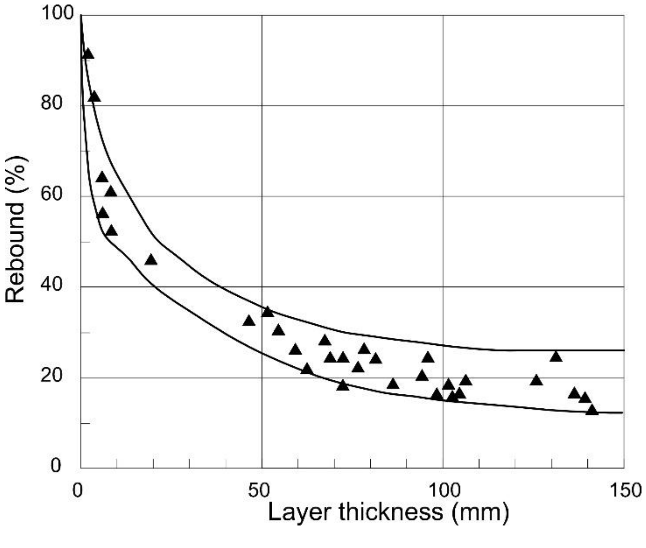

Fig. 7. Influence of layer thickness on rebound.

References

[1] . Mason, R. Mason, Shotcrete, in Tunnel Engineering Handbook, Van Nostrand Reinhold Comp.,1982, pp. 335-353.

[2] P. Teichert, Calcestruzzo spruzzato, E. Laich S.A., 1980, pp. 1-89.

[3] P. Wälchi, "Rückprallverminderung-staubreduktion", 56, Spritzbeton, Schweizerischer ingenieur und architekten verein, 1982, pp. 43-51.

[4] T. Ryan, 1st.. ed., Gunite a handbook for engineers, Cement and Concrete Association, 1973, pp. 1-63.

[5] American Shotcrete Association Underground Committee, "Encapsulation of reinforcement in tunnel shotcrete final linings", Shotcrete Magazine, vol. 22, no. 4, pp. 15-21, Fall 2020.

[6] W. Lukas, "Spritzbeton: Fehler, mängel und schäden; betontechnologidche unsachen", 3. Spritzbeton Kolloquium, September 27, 1991, Avegno, pp. 19-35.

[7] J. Rivas, Túneles y obras subterráneas, Sika S.A., 1996, pp. 1-207.

[8] J. Armengaud, et al., "Etude des paramètres influant sur les pertes de béton projeté par voie sèche", Journées Nationales de Géotechnique et de Géologie de l'Ingénieur, Juillet 2016, Nancy, pp. 1-8.

[9] S. Gérômey, Evaluation des paràmetres d'obtention de la qualité des bétons projetés utilisés dans de soutèrrements provisoires, des revêtements définitifs et des renforcements d'ouvrages, Thèse de Doctorat, Institut National des Sciences Appliquées de Lyon, Lyon, France, 2003, pp. 1-230.

[10] H. Hansen, et al, "Compressive strength of concrete-cube or cylinder?", Bulletin RILEM Matériaux et Construction Recherches et Essais, 17, pp.23-30, Décembre 1962.

[11] M. Aboud-Zeid, E. Elkhidir, "Influence of key parameters on quality of dry-mix shotcrete", Transportation Research Record, vol. 1798, pp. 51-55, January 2002. des Sciences Appliquées de Lyon, Mars 2005, p. 1-264.

[12] Y. Ishizeki, Y. Kato, "Study on the influence of shotcrete conditions on rebound", Seisan Kenkyu, vol. 69, no. 2, pp. 227-240, 2013.

[13] K. Guthoff, Einflüsse automatischer düsenführung auf die herstellung von spritzbeton, Doktorarbeit, Ruhr-Universität Bochum, Bochum, Deutschland, 1991, pp. 1-161.

[14] J. Marc, et al., The effect of spraying on fiber content and shotcrete properties, Shotcrete for underground support XII, 2015, pp. 1-15.

[15] O. Duckworth, "What's happening in there", Shotcrete Magazine, vol. 19, no. 3, pp. 28-32, Summer 2017.

[16] E. Yurdakul, K. Rieder, D. Granell, "An approach for improving the sustainability of shotcrete", Shotcrete Magazine, vol. 18, no. 2, pp. 32-37, Spring 2016.

[17] T. Ferguson, "A closer look at the benefits of predampening", Shotcrete Magazine, vol. 17, no. 2, pp. 48-50, Spring 2015.

[18] N. Ginouse, Étude fondamentale du processus de mise en place en béton projeté, Doctoral Thesis, The University of Laval, Québec, Canada, 2014, pp. 1-200.

[19] N. Banthia, H. Armelin, A novel double anchored steel fiber for shotcrete, Canadian Journal of Civil Engineering, vol 29, no. 1, pp. 58-63, February 2002.

[20] D. Beaupré, Reologhy of high performance shotcrete, Doctoral Thesis, The University of British Columbia, Vancouver, Canada, 1994, pp. 1-265.

[21] R. Schütz, Numerical modelling of shotcrete for tunneling, Doctoral Thesis, Imperial College, London, 2010, pp. 1-435.

[22] R. Bracamontes, "Understanding what can cause problems with concrete and shotcrete-Part 2", Shotcrete Magazine, vol. 21, no. 2, pp. 62-72, Spring 2019.

[23] L. Zhang, D. Morgan, S. Moalli, D. Gagnon, D. Dugas, "Tunnel shotcrete lining for hydroelectric projects", Shotcrete Magazine, vol. 21, no. 3, pp. 36-42, Summer 2019.

[24] Asociación Española de Túneles y Obras Subterráneas, Guía Técnica. Diseño, fabricación y puesta en obra del hormigón proyectado en obras subterráneas, Grupo de Trabajo WG-6 Hormigón proyectado, Junio 2014, pp. 1-107.

[25] Concrete Institute of Australia, Recommended practice shotcreting in Australia, 2nd ed., September 2010, pp. 1-84

[26] H. Kobler, “Dry-mix coarse aggregate shotcrete as underground support”, SP-14, 5th. ed., Shotcreting, pp. 33-58, 1987.

[27] R. Schütz, Numerical modelling of shotcrete for tunnelling, Doctoral Thesis, Imperial College London, London, UK, 2010, p. 1-435.

[28] G. Gullan, “Shotcrete for tunnel lining”, Tunnels and Tunnelling, vol. 7, no.5, pp. 37-47, September 1975.

[29] J. Royer, Etude de la mise en place et compaction du béton projeté, Thèse de Maîtrise, Université Laval, Québec, Canada, 2013, pp. 1-110.

[30] G. Girmscheid, et al., “Fully automated shotcrete robot for rock support”, Computer-Aided Civil and Infraestructure Engineering, vol. 16, no. 3, pp. 200-215, January 2001.

[31] U. Puri, T. Uomoto, “Properties of shotcrete (10)”, Seisan-Kenya, vol. 51, no.4, pp. 153-156, 1999.

[32] R. Linder, “Technologie des spritzbetons”, Beton-und Stahlbetonbau, pp. 63-67, März 1963.

[33] EFNARC, Guidelines for specifiers and contractors, European Federation of National Associations Representing Producers and Applicators of Specialist Building Products, 1999, pp. 1-35.

[34] M. Jolin, Mechanisms of placement and stability of dry process shotcrete, Doctoral Thesis, The University of British Columbia, Vancouver, Canada, 1999, pp. 1-166.

[35] A. Tripathi, K. Gahlaut, “A review paper on shotcrete technology”, International Journal of Cobined Research & Development, vol. 3, no. 1, pp. 33-37, July 2014.

[36] B. Lindlar, M. Jahn, J. Schlumpf, edition 2020, Sika sprayed concrete handbook, Sika AG, 2020, pp. 58.

[37] C. Resse, M. Venuat, Projection mortiers, betons et platres, Techniques et applications au bâtiment et aux travaux publics, Claude Resse et Mitchel Venuat, 1981, pp. 1-382.

[38] U. Diecken, Möglichkeiten zur reduzierung des rückpralls von spritzbeton aus verfahrenstechnischer und betontechnoogischer sicht, Doktorarbeit, Ruhr-Universität Bochum, Bochum, Deutschland, 1989, pp. 1-178.

[39] T. Melbye, Sprayed concrete for rock support, MBT International Underground Construction Group, 2001, pp. 1-127.

[40] American Shotcrete Association Underground Committee, “Spraying shotcrete overhead in underground applications“, Shotcrete Magazine, vol. 21, no. 3, pp. 45-49, Summer 2019.

[41] J. Scherer, “Instandstellen und verstärke von betonbauteilen, Trockenspritzverfahren für reparaturen”, Schweizer ingenieur und architekt, 43, pp. 1086-1090, Oktober 1986.

[42] M. Ballou, “Shotcrete rebound-How much is enough?“, Shotcrete Magazine, vol. 11, no. 2, pp. 44-45, Spring 2009.

[43] B. Maidl, M. Thewes, U. Maidl, 1st.. ed., Handbook of Tunnel Engineering I. Structures and Methods, Editorial Wilhelm Ernst & Sohn Verlag fur Architektur und Technische, 2013, pp. 1455.

[44] American Shotcrete Association Underground Committee, “Mechanical application of shotcrete in underground construction“, Shotcrete Magazine, vol. 22, no. 4, pp. 22-28, Fall 2020.

[45] N. Ginouse, M. Jolin, B. Bissonnette, “Effect of equipment on spray velocity distribution in shotcrete applications”, Construction and Building Materials, vol. 70, pp. 362-369, November 2014.

[46] H. Armelin, et al., “Rebound in dry-mix shotcrete”, Concrete International Design and Construction, vol. 19, no. 9, pp. 54-60, January 1997.

[47] H. Parker, G. Fernández-Delgado, J. Jori, “A practical new approach to rebound losses”, SP-54, Shotcrete for ground support, 1977, pp. 149-187.

[48] K. Robertson, P Giguére, N. Nda-Ngye, “Société de transport de Montréal-Metro yellos line tunnel repairs“, Shotcrete Magazine, vol. 18, no. 1, pp. 30-33, Winter 2016.

[49] G. Girmscheid, S. Moser, “Fully automated shotcrete robot for rock support “, Computer-Aided Civil and Infrastructure Engineering, vol. 16, no. 3, pp. 200-215, December 2002.

[50] W. Brown, Engineering and design. Standard practice for shotcrete, US Army Corps of Engineers, 1993, pp. 1-48.

[51] J. Wang, et al., “Durability performance of brine-exposed shotcrete in salt lake environment”, Construction and Building Materials, vol. 188, pp. 520-536, November 2018.

[52] V. Bindiganavile, N. Banthia, “Effect of particle density on its rebound in dry-mix shotcrete”, Journal of Materials in Civil Engineering, vol. 21, pp. 58-64, February 2009.

[53] J. Wang, et al., “Mechanical properties permeability and durability of accelerated shotcrete”, Construction and Building Materials, vol. 95, pp. 312-328, October 2015.

[54] C. Mircea, O. Corbu, E. Maier, C. Rus, “Rehabilitation of the Suhurlui irrigation pipeline“, Shotcrete Magazine, vol. 19, no. 1, pp. 42-45, Winter 2017.

[55] H. Armelin, Rebound and toughening mechanisms in steel fiber reinforced dry-mix shotcrete, Doctoral Thesis, The University of British Columbia, Vancouver, Canada, 1997, pp. 1-285.

[56] D. Morgan, Advances in shotcrete technology for support of underground openings in Canada, SP-54, Proceedings of the engineering foundation conference, June 3-7, 1990, Uppsala, Sweden, pp. 350-382.

[57] N. Ginouse, M. Jolin, B. Bissonnette, “The effect on fiber content and shotcrete properties”, Shotcrete for underground support XII, 2015, pp. 1-15.

[58] N. Ginouse, Étude fondamentale du processus de mise en place en béton projeté, Doctoral Thesis, The University of Laval, Québec, Canada, 2014, pp. 1-200.

[59] V. Bindiganavile, N. Banthia, “Fiber reinforced dry-mix shotcrete with metakaolin”, Cement & Concrete Compositest, vol. 23, no. 6, pp. 503-514, 2001.

[60] J. Armengaud, et al., “Characterization of fresh dry-mix shotcrete and correlation to rebound”. Construction and Buildings Materials, vol. 135, no. 15, pp. 225-232, March 2017.

[61] Kalhori, B. Bagherzadeh, R. Bagherpour, M. Akhlaghi, “Experimental study on the influence of the different percentage of nanoparticles on strength and freeze-thaw durability of shotcrete, Construction and Building Materials, vol. 256, pp. 1-13, September 2020.

[62] M. Khoshechin, J. Tanzadeh, “Experimental and mechanical performance of shotcrete made with nanomaterials and fiber reinforcement, Construction and Building Materials, vol. 165, pp. 199-205, March 2018.

[63] A. Gagnon, I. Fily-Paré, M. Jolin, “Rethinking shotcrete mixture design through sustainableingredients“, Shotcrete Magazine, vol. 18, no. 4, pp. 28-31, Fall 2016.9

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