Automation for Crushing and Screening Equipment to Produce Graded Paving Crushed Stone

Anatoly Tikhonov¹ and Vladimir Velichkin¹

¹Moscow State University of Civil Engineering, Yaroslavskoye Sh. 26, Moscow, Russia, 129337
e-mail: VelichkinVA@mgsu.ru

Abstract. This paper offers analysis of factors related to production and storage of graded crushed stone, which adversely impact the service life and wear resistance of asphalt-concrete motor road pavements. The paper describes external and technology-related parameters that may cause changes of the preset ratio in graded crushed stone. Control factors are described that ensure the formulated fraction ratio in crushed stone by controlling the operation mode of the crushing and screening equipment. The paper also contains an ACS flow chart for crushing and screening equipment engaged in continuous closed-cycle two-stage technology. Performance of the ACS to maintain the preset fractionated crushed stone ratio has been confirmed with a mathematical model.

1. Introduction

Increasing cargo and passenger traffic of the recent years in the Russian Federation has caused dramatic deterioration in the condition of asphalt-concrete pavements on both arterial and local motor roads. The problem of motor road quality was proved by President of the Russian Federation during his latest annual Direct Line TV program (14.04.2016).

It is known that apart from the technological operations, the quality of asphalt-concrete mix, and the service life and wear resistance of asphalt-concrete pavement (bottom layer, top layer, and surface finish), largely influenced by the quality of filler material, also depends on how they are made and then stored in warehouses that have galleries, partitions, conveyer belts, discharge bridges, etc. used to operate the crushing and screening equipment (CSE) [1].

Use of warehouses to store ready-to-use graded crushed stone (GCS) incurs considerable capital and operation costs. In addition, as GCS undergoes accumulation, storage and handling in warehouses, this reduces its quality, thus affecting wear resistance of the road topping.

In the set of activities to produce concrete mixes, one of the critical tasks is to improve the production process used to make large graded aggregate (graded crushed stone), and the related stocking and processing costs amount to 30-40% of the ultimate cost of hard road topping [2].

When in storage, ready crushed stone is exposed to these quality-risk factors: contamination, face rubbing in the course of warehouse handling, grinding during bulldozing, high humidity, impact by the elements (freezing-melting cycle), all of which causes loss of grain strength, disintegration during transportation, fraction mixing, and oxidation by the air.
2. Methods. An Experimental section

In most cases, contamination, oxidation and face rub of crushed stone grains make the surface less ready to interact with organic cementing materials.

\[ E_p = f(L, x, z), \]

where \( E_p \) – power budget and activity of crushed stone; \( L \) – specific surface; \( x \) – rock chemistry (acid/base); \( z \) – extent of contamination (purity), oxidation.

The amount of moisture the rock material can absorb depends on the time factor, and the dependency is described by this equation:

\[ W = aln t + c, \]

where \( W \) – water absorption, % by weight; \( c \) – water absorption, % by weight in the first day; \( a \) – the factor of crushed stone grain structure; \( ln \) – natural logarithm.

Power budget of crushed stone tends to shrink in storage as contamination grows while rubbing and grinding reduce the specific surface.

Exposure of crushed stone to frost causes not only degradation but also irreversible changes of the structural-mechanical grain properties of the crushed stone. Changes of crushed stone strength under natural factors were assessed experimentally based on its extent of degradation by repeated impact. Stone became more crushable after water saturation. Water saturation of crushed stone grade “400” was 7-8%; with such water content one can expect internal structure disintegration by frost impact [3].

Generally, crushed stone strength and service life of the road topping depend on two factors at once: moisture and freezing [4].

As requirements to aggregate quality grow, improvement of the technology should envisage less processing of ready graded crushed stone by doing without any cumbersome and expensive warehouses to store building components for the asphalt-concrete mix.

This eliminates the negative influence that warehouses may bear on technical and economic performance and the quality of aggregate; this also creates conditions to manufacture high-quality mix thanks to: better adhesion of fine-crushed aggregate with non-rounded cubic grain shape, and because there is no oxidation, contamination or litter to prevent adherence with cement.

Long service life and wear resistance of asphalt-concrete topping on motor roads much depends on the quality of fraction-graded crushed stone (FGS), used along with bitumen to produce asphalt-concrete mixes.

The production process of GCS operation should rely on the principle of continuous FGS manufacturing, based on mix proportion formulation as large-grain aggregate is fed to the mixers immediately after crushing, by passing the interim storage phase. For continuous manufacturing with preset ratio, the CSE must work along with the mixer, and this dramatically changes the existing process of mix manufacturing.

To implement the preset-ratio continuous FGS manufacturing that works to reduce costs and improve mix properties thanks to high-quality aggregate, the crushing process should be further improved by developing a controlled production process (CPP), with various mix formulations (sets) that call for CSE operation mode changes and factors that impact the grain structure.

Whereas CSFR should be measured for production purposes, due to transition from one to another type of asphalt-concrete top (formulation), (e.g., \( y_1 = 5 - 15 mm, y_1 = 15 - 25mm, y_1 = 25 - 40mm \)) CSFR changes in the course of crushing under external factors related to changing physical-mechanical properties of the source rock, which include:

- variations of physical-mechanical properties of source rock in the ground layer of the same quarry;
- changes in strength of limestone and granite to be crushed;
- extent of load on the crusher’s chamber;
- lump size of source rock being processed;
- condition of impacting elements of the mechanical equipment.

Operation analysis of the production system for two-stage continuous operation crushing process demonstrated that it was virtually impossible to ensure the preset formulation of crushed stone fraction.
within the required range, considering existing disturbing factors related to changes of physical-mechanical properties of source rock and numerous assortment (formulations) of construction mixes (10 to 200), as defined in consumer’s production tasks [3].

System processes are so complex that the operator is unable to respond to changes in the crushed stone fraction structure in time and correctly in order to make adjustments as required.

This issue can only be resolved if one uses automated control of the production equipment for the continuous operation crushing and screening unit with ongoing monitoring and adjustment of preset fractions. Serial-manufacture mobile GCS, widely used for road construction, do not have controls that enable to automatically control the crushing process for achieving the preset fraction ratio in the crushed stone (CSFR). It is an important R&D activity to create a controlled flexible technology where the operator does not have to manually readjust operation modes of the crushing and screening equipment that ensures production of the preset crushed stone fraction ratio as material is continuously supplied into the batch-mixing unit bypassing the interim storage phase [5].

The controlled crushing production process should ensure the entire automation system’s compliance with the stringent criteria under formulation regulating GOST 9128-86 on crushed stone fraction ratio regardless the physical-mechanical properties of rock. This is a R&D direction that helps to theoretically base and design a stabilizing ACS (automatic control system) for production equipment for crushing and screening. An important link in the solution chain is a crushing system, where the optimal criterion is the minimum of equipment enabled with an automatic control system (ACS). Just as important stage in ACS design is to determine the control stimulus (CS) and to alter their parameters that ensure achievement of the formulation-preset mix of CSFR (crushed stone fraction ratio). Changing the size of the discharge hole during first crushing also changes the fraction ratio and increases/decreases the yield of all fractions at once without changing the ratio. Of greatest interest is the work of secondary crushers in the closed cycle to determine the CS, thus ensuring changes of CSFR. An efficient CS to change the CSFR is to supply a controlled volume of oversize crusher material with different grain structure relative to aggregate fraction.

The simplest option is the shutter design to control proportions of oversize material (>40 mm) (Figure 1). There is a divider installed in the housing that divides the flow to the preset extent. The motor is driven by an electric screw drive that connects to the electric motor through a reduction gear. The divider is registered by sensors.

Oversize crushed stone in control volume is supplied to crushers $D_h$ and $D_k$. Output of separate crushed stone fractions (GCS) in the closed crushing system, with breakdown by cycles will be (Figure 2):

$$S_1, S_2$$

Where $Y_{p31}, Y_{p41}, Y_{p32}, Y_{p42}, Y_{p33}, Y_{p43}$ – output of GCS in direct cycle from secondary crushers: last digits – GCS ID, first – ID of supplying crusher; $q_{23}, q_{24}$ – output of oversize material from secondary crushers – index 2, indexes 3, 4 – crusher IDs.

The partitioned feed mode is adequate for parallel operation of two variable-performance crushers of different types. The finer is the source material, the more regular is its distribution over sections; as a result, overlap of grain characteristics occurs, which greatly expand their functionality to address the main problem: achieving the preset CSFR with the CS in the TPP (see Figure 2), with the shutter $\varphi_2$ and crusher’s discharge hole (CDH) $S_1$. Crushers work in the two-stage CPP where the flow is controlled by the CS ($\varphi_2$), while the CDH is controlled at first crushing from $S_{1\text{min}}$ to $S_{1\text{max}}$. Likewise, one can determine efficient control commands and grain characteristics in the production system for two first crushers that work in open mode with shutter $\varphi_1$ and two secondary shutters – in close crushing cycle with shutter $\varphi_2$ (Figure 3).

Analytic expression of output of large-grain aggregate for any fraction for such technology will appear as: see formula (2).

Analysis of grain characteristics obtained from two-stages
\[
\gamma_{d2i} = \left[ \gamma_{p3i} \cdot (1 + \sum^n q_{23}^n) \right] \cdot \left( 0.5 - \frac{r}{B} \cdot \sin \alpha \right) + \left[ \gamma_{p3i} \cdot (1 + \sum^n q_{24}^n) \right] \cdot \left( 0.5 + \frac{r}{B} \cdot \sin \alpha \right) \\
\gamma_i = \left[ \gamma_{d1i} \cdot (1 - \psi_1) + \gamma_{d2i} \cdot \phi_1 \right] + \left[ q_{11} \cdot (1 - \varphi_1) + q_{12} \cdot \varphi_1 \right] \times \left[ \left( \frac{\gamma_{p3i}}{1-q_{23}} \right) \cdot (1 - \varphi_2) + \left( \frac{\gamma_{p3i}}{1-q_{24}} \right) \cdot \phi_2 \right] \\
\varphi_2 \right] \\
Q_1: Q_{\min} - Q_{\max} \left[ \frac{m^3}{\text{hour}} \right]; \\
S_1, S_4 = 40 - 100 \, \text{mm} \quad \varphi_1, \psi_2, \psi_3: 1, 0.75, 0.5, 0.25, 0; \\
V_2 = 400 - 1800 \left[ \frac{r}{\text{min}} \right]; \\
GSE_1, GSE_2, GSE_3: 1, 2, 3, 4, 5; \\
S_3 = 15 - 50 \, \text{mm}; \\
P_c = d_c \cdot t_c [M^3]; \\
P_R = d_R \cdot t_K [m^3] \\
Q_0 = 12 m^3 \\
\text{CRIA} \, \text{– microprocessor; Y} \, \text{– bidirectional tool changer; NB} \, \text{– storage bins} \ V_0 = 12 m^3 \\
\]

Figure 1. Shutter to control flow of aggregate enabling crushers to process grain sizes of variable characteristics
1- body; 2 - divider; 3 - cylinder; 4 – electric motor; 5 – reduction gear; 6 - contactless sensors of divider position.

Figure 2. Diagrams of GCS output \( \gamma_3 \) in two-stage closed-cycle crushing production process (CPP)
Figure 3. Flow chart of ACS for two-stage closed-cycle crushing production process

Analysis of grain characteristics after the two-stage closed-cycle crushing production process demonstrates that average fraction $\gamma_2$ varies over a minor range of 30 to 40%, and 28 to 56% for $\gamma_3$; this creates extra problems with controlling this fraction ratio. This creates the need to use the surplus of fraction $\gamma_3$ (see Figure 3) to make up for fractions $\gamma_1$ and $\gamma_2$, as an additional control factor. As a result, one can establish optimized action by CS: see formula (3)

$$CS(Q_1) = \text{control of first batch; } CS(S_1), CS(S_3), CS(S_4) = \text{changing the size of the discharge hole respectively for first jaw-type crushe, secondary cone-crusher and jaw crushers; } CS(V_1) = \text{controlling circumferential speed of the rotor’s impact bars on first hammer crushe}; \phi_2 = \text{adjusting the processing volume of oversize material (>40 mm) at secondary crushing shutter (see Figure1); } \phi_3^{Kp1} = \text{adjusting the volume of processed source material at first crushing; } \phi_3 = \text{changing processing volume of surplus GCS } \gamma_3 \text{ and/or } \gamma_2 \text{ at secondary crushing in closed cycle; } dk \text{ and } dc = \text{size of discharge hole for respectively large and medium GCS to process surplus } P_K \text{ and } P_c \text{ through shutter } \phi_3.$$

Variety of controls, each of which follows a specific dependency to influence the CSFR (control parameters $\gamma_1, \gamma_2$ and $\gamma_3$), and considering the time factors of delayed transportation in the production line, create a fairly complex dynamic automated control system for the crushing production process (CPP). Addressing this issue greatly facilitates mathematic modelling; inputs for program development include:

- Fundamental characteristics of grain crushers: $\gamma_1 = f(d_0)$;
- Condition of shutters $\phi_1, \phi_2, \phi_3$, changing the feed hole “B” at interval: 1,0.75,0.5,0.25,0;
- Total grain characteristics in crushe found by overlay method $\gamma_1 = f(s)$;
- Diagrams of CSFR changes for crushing of surplus with fraction $\gamma_3$ (or) $\gamma_2$: $\gamma_{gi} = f(\phi_3)$, etc.

To rule out influences on the process to control delayed transportation, the technology provides storage hops to hold $Q = 12m^3$, ensuring CSFR in the range of $Q_{min} \geq 2m^3$ and $Q_{max} \leq 12m^3$ by adjusting the CS; this includes crushing of surplus (> $12m^3$) with intensity $P_c$ for fraction $\gamma_2$ and/or $P_K$ for fraction $\gamma_3$ along with oversize material $\gamma_4 > 40mm$. Controlled CPP adjusting preset parameters ($\gamma_1$, $\gamma_2$ and $\gamma_3$) produces freshly crushed stone at the same time in the proportion of preset mix formulation. Here the purpose of ACS two-stage closed-cycle crushing production process is to maintain three GCS preset levels in the hops by sensor readings at the same time. Initial adjustable parameters should be optimized ensuring that the CSFR stays close as possible by weight to the adopted formulation. Signals from CSFR level meters are received by $P_i(CIRAK)$ microprocessor, and then signals to respective CS are generated depending on the GCS ratio.
Design of an automatic control system calls for detailed examination of the object’s dynamic properties, with a mathematical model built; this helps to specify parameters of control factors and work out a control algorithm ensuring continuous quantity control of CSFR by mix formulation.

Realizing a mathematical model helps to objectively consider the specifics of a control system for closed-cycle crushing technology, build related control algorithms, and define the parameters to control graded crushed stone ratio also factoring in the transportation delay of the specific production line.

Crushed stone is discharged through trap doors \( \gamma_1, \gamma_2, \gamma_3 \) in quantities required by the formulation. The control system maintains the required level in the hoppers, responding to signals from strain level meters set to control mean (optimized), maximum and minimum permissible levels in each hopper.

As follows from the system’s description, actuators used to control the fraction structure are distribution shutters \( \gamma_{4s}, \gamma_{5s}, \gamma_{6s}, \gamma_{7s} \), trap doors \( \gamma d_1, \gamma d_2 \); first material feed; bypass intensity from hoppers \( \gamma d_3, \gamma d_4 \), control of jaw-type crushers \( S_1, S_2 \), and cone-type crushers \( S_3 \) and impact bar rotation speed of rotor-type crushers \( V_p \) by the discharge holes.

The control system has ample adjustment functions to enable any formulation as may prove necessary. However, this also generated some issues to overcome as the control system is designed. First of all, one needs to determine the initial setup of actuator parameters.

Following that, one needs to decide which exactly actuators, and in which ranges, should change their parameters responding to various failures of stable fraction output. Here the problem is complicated by actual transportation delay on the first and secondary crushing lines; therefore, changing actuator control parameters influence the changing level of crushed stone in different fractions in the hoppers during a specific time period, as this may adversely influence the rate of ready crushed stone output to the user.

Mathematical description of the system may present actual continuous processes in the discrete form, with specific short time interval \( \Delta t \). Then to fill a hopper holding the fraction numbered \( j = 1, 2, 3 \) \( (j = 4 \) stands for oversized fractions supplied for secondary crushing) at time point \( t_{i+1}=t_i+\Delta t \) is written out as this dependence:

\[
P_j(t_i + 1) = P_j(t_i) + \int_{t_i}^{t_i+1} \left( Q_1 q_{j,1} \right)_{t-T_1} dt + \int_{t_i}^{t_i+1} \sum_{n=0}^{\infty} \left( Q_1 q_{4,1} q_{r,2} q_{j,2} \right)_{t-T_1} dt - (n + 1)T_2 dt + \int_{t_i}^{t_i+1} \sum_{k=2}^{\infty} d_{2,k} q_{2,k} f(q_{j,3}) dt - Q_{2,j} d_{2,j} \Delta t - d_{0,j} Q_{0,j} \Delta t - (4)
\]

where: \( f(q_{j,3}) = \left\{ \begin{array}{l} q_{i,j}, \text{if } k - j > 0; \\ 1 - \sum_{i=1}^{j} q_{i,j}, \text{if } k - j = 0; \\ 0, \text{if } k - j < 0; \end{array} \right. \)

\( T_1 \) – time that takes crushed stone to pass the route: loading – first crushing – sieve – hopper;
\( T_2 \) – time that takes crushed stone to pass the route: sieve – secondary crushing – sieve;
\( d_{0,j} \); \( d_{2,j} \); \( d_B \) – condition of crushed stone discharge shutters, respectively, sent to dump, to secondary crushing, and discharge by formulation \( (d=0 \) shutter closed; \( d=1 \) shutter fully open);
\( Q \) – source material supply rate;
\( Q_{0,j} \); \( Q_{2,j} \) – crushed stone discharge rate, respectively, sent to dump, and to secondary crushing;
\( QB \) – total rate of crushed stone discharge by all fractions (unit’s output);
\( R_{j} \) – relative content of fraction as per formulation;
\( q_{j,k} \) – grain characteristic of first or secondary crushing system, with distribution shutter numbered “\( k \)” as entry, see Figure1;

integrals that are part of formula \( (4) \) are found using the rectangle method. In the second integral, “\( n \)” totaling is done until the next item becomes smaller than the preset small integer \( \epsilon \), provided that condition \( t - T_1 - (n + 1) \geq 0 \) is observed.

Hopper filling levels and conditions of controls are printed out at interval \( \Delta T \).

The controlling function is reduced to maintaining a certain level inside hoppers.
Filling the j-th hopper at point of time t is the function of $\gamma_j$, which depends on preset system parameters.

$$\gamma_j = \gamma_j(t, b, Q_1, \varphi_1, \varphi_2, \varphi_3, d_{hs}, d_{hm}, d_{hl}),$$

where $j=3, 4, 5$ correspond to hoppers with small, medium and large fractions.

Therefore, control should achieve the ratio of $\gamma_j(t, b, Q_1, \varphi_1, \varphi_2, \varphi_3, d_{hs}, d_{hm}, d_{hl}) = c_j$, where $c_j$ are constants for any $j$.

For $\gamma_j - c_j > 0$, for any $j$, we input parameter $b=1$; if the ratio is true for all, we input $Q_1 = Q_{min}$.

For $\gamma_j - c_j < 0$ for any $j$, we input $Q_1 = Q_{normal}$.

For $\gamma_j - c_j > 0$ for one of $j$, to match the given $j$, we open one of the shutters $d_{hs}$ to damp, or $d_{hm}$, $d_{hl}$ to bypass.

For $\gamma_j - c_j < 0$ for one of $j$, the respective shutter gets closed.

For each formulation, we select specific values for shutter position; then the interpolator defines $\varphi_i$ – rate of opening of the trap door.

The mathematical model of the crushed stone fraction production process was used to check output for mix formulation $R_4$ (example: $\gamma_{R1}=50\%$, $\gamma_{R2}=25\%$, $\gamma_{R3}=20\%$) with output by weight $P_i = \gamma_{Ri} \times Q$, m$^3$ for the crushed stone fraction (Figure 4).

The diagrams show that during 480 min (one work shift) no practically component of crushed stone fraction, weighing $P_i$ ever went beyond the preset range of $2 \geq P_i \geq 12$ m$^3$, even though fluctuations of all crushed stone fractions were rather considerable during the time period.

The GCS mathematical model suggests that the automatic control system based on controlling actions helps to support controllable two-stage closed-cycle crushing production process, where the source data is the output of the first crushing, and the output data is the large aggregate fraction preset in the mix formulation.

![Figure 4. Diagram representing changes in crushed stone fraction ratio of preset formulation in the course of control of production equipment parameters.](image)

3. Conclusions

Once adopted, the automatic control system for the two-stage closed-cycle crushing process without large warehouses for temporary storage of ready graded product helps to achieve the following:

- Improving the mix quality, and respectively, wear resistance and long service life of asphalt-concrete pavement thanks to stronger adhesion of freshly made graded crushed stone to bitumen;
- Ensuring high quality of graded crushed stone thanks to prevented oxidation of grain surfaces and weaker properties after freezing and defreezing; producing crushed stone with cubic grain shape, and preventing face flattening by rubbing during bulldozing;
- Reducing considerably (to 45%) capital and operation costs of construction and maintenance of expensive temporary storage warehouses for graded crushed stone.

References
[1] Arutiunian V O and Gorelishev N V 1990 Improving Processing of Stone Materials and Ways of Use in Road Construction Papers of Soyuzdornii Issue 70
[2] Biroslovskiy Ya M, Kolker I Ya and Kurdenkov B I 1997 Processing and Concentrating Mineral Materials and Production Automation (Moscow, Transport Publishers)
[3] Berzishev A A, Vasilyev V N and Volkov V G 2008 Production of Nonmetallic Construction Materials. Condition and Improvements (Moscow, Gosstroyizdaniye Publishers)
[4] Kurdenkov B I, Poliakova A I and Filatov A P 2002 Concentration of Stone Materials for Road Building (Moscow, Avttransizdaniye Publishers)
[5] Tikhonov A F, Kononikhin B D and Kosarev A I Organization of Material Processing Control A.c. No. 1680327 IB No. 36 dated 30.09.1991