Journal of Materials and Applications 2020;9(2):70-78
https://doi.org/10.32732/jma.2020.9.2.70

The Effect of Atmospheric Pollution on Building Materials in the Urban Environment

Andrey A. Kuzmichev, Valery N. Azarov, Alexander V. Kuzmichev

Institute of Architecture and Civil Engineering, Volgograd State Technical University (VSTU), Akademicheskaya st.,1, 400074, Volgograd, Russia
E-mail: andrew_9207@mail.ru (Corresponding author); azarovpubl@mail.ru

Received: 10 April 2020; Accepted: 28 April 2020; Available online: 30 June 2020

Abstract: Nowadays atmospheric pollution affects not only the urban environment in general, but building materials, which leads to their corrosion, in particular. The article discusses the regularities of the adhesion process of particulate matter (dust) on the vertical surfaces of buildings and structures, which are made of various building materials. On the basis of experimental studies, regression dependences of the adhesion of urban dust on different vertical surfaces from random determining factors were obtained. Thus, by studying the regularities of pollution of urban environment objects, made of various building materials, it is possible to achieve their preservation, since they demonstrate the architectural and design features of various historical periods of the country's development.
Keywords: Building materials; Atmospheric pollution; Pollution of buildings; Pollution of building materials; Dust; Particulate matter; Dust adhesion; Urban vertical surfaces.

1. Introduction

Currently, there is an increased level of background concentrations of pollutants in the urban air environment, which is caused by ecological factors and increases annually to a greater extent due to anthropogenic processes, such as industry, transport, housing and communal services. Polluted air affects not only people's health, but also on the objects of the urban environment. Thus, by studying the regularities of pollution of urban environment objects, made of different building materials, it is possible to achieve their preservation, since they demonstrate the architectural and design features of various historical periods of the country's development.

The damage caused by air pollution on building materials is indeed a matter of serious concern since the service life of buildings is significantly reduced. Indeed, the intensity of the impact of technogenic pollutants on the degradation of buildings is greater than the impact of natural pollutants. Most importantly, the effects of pollution, degradation, corrosion and erosion caused by SO_2 are very serious. The effects of air pollution on materials can be considered in terms of material loss, discoloration, contamination, structural failure and others. Both discoloration and structural failure due to air pollution in buildings can be negligible. But the effect of corrosion due to acid deposition is a much bigger problem. Especially significant is the effect of emissions of sulfur dioxide and nitrogen dioxide. Let us consider the effect of the main atmospheric pollutants on the state of building materials [1].

1) Oxides of sulphur is an aggressive gas coming from the chemical and paper industries when it reacts with the atmosphere and causes acid rain. The most prominent pollutant responsible for metal corrosion is sulfur dioxide, and it has been reported that corrosion of solid metals such as steel begins at an average annual concentration of 0.02 ppm. Sulfuric acid mist in the atmosphere causes a deterioration in the quality of structural building materials, such as marble sculptures and buildings, which have suffered over the past 30 years as a result of the increased content of SO_2 in the atmosphere [1].

2) Carbon monoxide. Along with the very important role of SO_2 for a number of materials, studies of the direct or synergistic effect of NO_x, CO, and O_3 also contributed to the understanding of the complex effects of pollution [2]. The burning of fossil fuels leads to the release of various pollutants into the atmosphere, the main of which are SO_x, NO_x and CO. In particular, the main sources of CO in urban air are smoke and exhaust fumes from many coal, gas or oil burning devices. These puffed emissions have a large effect on structures located exclusively near the plants from where they are emitted [1].

3) Nitrogen oxides are formed during the burning of fossil fuels and are responsible for acid rain when they react with the atmosphere. Acid rain has a huge effect on the surface of building material [1]. As an air pollutant, it works in several interconnected ways. At short-term concentrations in excess of 200 $\mu g/m^3$, it is a toxic gas that causes significant airway inflammation. NO_2 is the main source of nitrate aerosols, which form an important

fraction of $PM_{2.5}$ and, in the presence of ultraviolet light, ozone. The main sources of anthropogenic emissions of NO_2 are combustion processes (heating, power generation, engines of vehicles and ships) [3,4].

4) Ozone. Most of the degradation of building materials is currently attributable to weathering, caused mainly by ozone. Ozone is present in two layers of the atmosphere. The part of Ozone that is present in the lower atmosphere (troposphere) is more dangerous than the part that is present in the stratosphere. Ozone present in the stratosphere prevents the fall of ultraviolet radiation on the ground, since it has an adverse effect on structures [1]. It is formed by reaction with sunlight (photochemical reaction) of such pollutants as nitrogen oxides (NO_x) from emissions from vehicles and industry and volatile organic compounds (VOCs) emitted by industry, vehicles, solvents and others. The highest levels of ozone pollution are observed during periods of sunny weather [3,4].

5) Particulate matter. One of the main ecological factors that negatively affect the atmospheric air and, as a consequence, the environment, is particulate matter (dust). These are particles of natural and anthropogenic origin that are in the air under the influence of air currents and settle on various surfaces together with precipitation or under the influence of gravity [5-7]. In 2016, it is estimated that air pollution (both in urban and rural areas) resulted in 4.2 million premature deaths worldwide per year. This mortality is due to exposure to small solid particles PM_{10} and $PM_{2.5}$ (10 μm and 2.5 μm or less in diameter, respectively), which cause cardiovascular and respiratory diseases [3,4].

2. Materials and methods

2.1 The relationship between the adhesion of particulate matter and the properties of building materials

One of the main processes that takes place in atmospheric air and negatively affects the appearance of buildings and structures is the adhesion of particulate matter (dust). It is the interaction of particles with a solid surface, due to forces depending both on the properties of the contacting bodies and on the properties of the environment [8–11]. In the absence of adhesion, dust during its deposition on various surfaces would continuously return to the atmosphere due to air flows, and its concentration in atmospheric air would reach a huge value [8–11].

The following types of building and finishing materials are most often used for arranging facades of buildings and structures: plaster (mineral, acrylic, silicate, silicone), facade paint (acrylic, silicone, silicate paint for outdoor works), natural and artificial stone (marble, granite, sandstone, dolomite), finishing brick (silicate, ceramic, clinker), facade tiles (ceramic, concrete), facade cassettes (steel, aluminum), porcelain stoneware, glass panels, etc. Operational characteristics of varnish juicy coatings to a large extent depend on their interaction with the substrate, that is, on the type of bonds between the material and the substrate. When applying paint and varnish material on a solid surface, an adsorption interaction is established between them, the degree of which determines the completeness of wetting of the surface, which largely determines adhesion, continuity, optical, anticorrosive and other properties of the coating. Let’s consider the basic properties and design features of the vertical surfaces of buildings and structures made of various building materials that affect the process of dust adhesion on objects of the urban environment.

1) Surface cleanliness. The surface of almost any solid bodies contains various contaminants (particulate matter) and impurities (adsorbed gases, air moisture). For metals (except gold, platinum, silver), typical contaminants are oxides. For all metals containing oxide layers, the presence of physio- and chemisorbed water is inherent due to sorption ability, the amount of which reaches several tens of monolayers, depending on the adsorption activity of the metal and air humidity. When applied to metal surfaces, the paint material does not come in contact with the metal itself, but with oxygen or other compounds and adsorbed water on its surface. When studying glass surfaces, it was found that they are enriched in silica and the presence of silanol groups, which are hydrogen donors, is characteristic, therefore, as in the case of metals, water is chemisorbed on the glass surface. On the surface of silicate building materials (concrete, plaster, brick, stone), there is always adsorbed water, as well as carbonates due to carbon dioxide of the air, because building materials are alkaline in nature [12,13]. It is known that layers of a substance adsorbed on a surface can alter the molecular interaction. Despite the fact that the adsorption layers do not have a noticeable effect on the electric forces arising due to the charge of the double layer, but if these layers report surface conductivity, it is possible to expect a decrease in the Coulomb interaction over time. Surface moisture promotes capillary condensation in the gap between the contacting bodies [10]. There are various methods for cleaning surfaces. Glass surfaces are recommended to be cleaned with a chrome mixture, and then with water, or distilled water with acetone. Steel surfaces are cleaned with silica gel, carbon and B-70 gasoline, activated carbon and ethanol, alloyed chrome vanadium steel surfaces are offered to be cleaned with acetone. The final step in cleaning a hard surface is to treat it with an organic solvent. For particularly thorough removal of contaminants, the method of cleaning with a flame or in a smoldering gas (argon atmosphere) discharge is used, with this method, organic impurities are burned out. Painted surfaces must not be treated with heat, solvent, activated carbon, as dissolution, softening, damage to the coating occurs. From painted surfaces, contaminants are removed using distilled water [10].

2) Hydrophilicity and hydrophobicity of the surface are properties that characterize the affinity of solids to water. According to Rebinder P.A., metals are hydrophobic in their molecular structure, but oxides and sorbed gases give their surface hydrophilicity. For example, the maximum swelling of wood is observed in water. With a decrease in dielectric constant, the degree of absorption of the corresponding liquids decreases. However, wood practically does not swell in aromatic and aliphatic hydrocarbons, only capillary absorption of these compounds occurs [14].

Plastics, depending on the chemical nature of the binder, have a surface of different polarity. So, organic glass, polyamide, polyacetate plastic masses of pheno- and aminos are well wetted with aqueous solutions of film formers. However, problems arise when applying paints containing polar solvents to polymers with high surface hydrophobicity, such as polyolefins, polyfluoroolefins. Thus, a hydrophilic surface is needed for water-based paints, and a hydrophobic one for hydrophobic film former paints [14]. Regulation according to the sign of the polarity of the surface is achieved by the following measures: hydrophilization - by thorough degreasing, oxidation (in the case of plastics), applying conversion coatings (in the case of metals); hydrophobization - by treatment of surfactant surfaces, finishes, grinding of the surface in the presence of non-polar liquids (for metals) [14].

3) Surface roughness. The microrelief or atomic-molecular surface roughness is determined by the crystalline and supramolecular structure of the material itself. In addition, surface cracks and cavities of micro- and submicroscopic sizes are characteristic of crystalline bodies. The macrorelief of the surface is determined by the nature of the material and the conditions of manufacture and processing of products. Varieties of macrorelief are waviness, roughness, porosity. The relief can be created due to surface defects - risks, scratches, sinks. Data on the surface geometry is obtained by taking profilograms (a set of irregularities forming the surface microrelief) [15]. The surface roughness is determined on the basis of GOST 2789-73 [16], using altitude and step parameters. Altitude parameters (R_a is the arithmetic mean deviation, R_z is the maximum height of the profile, R_{max} is the total height of the profile) characterize the average and maximum height of the bumps, step (S is the average step of the local protrusions of the profile, S_m is the average step of the bumps, tp is the relative reference length of the profile, where p is the value of the profile cross section level) characterize the mutual arrangement of the peaks of the irregularities. 14 classes of surface roughness (purity) were determined. The highest (purest) class is 14. It corresponds to a surface with values of $R_a = 0.01$ μm and $R_z = 0.05$ μm. The surface relief affects the consumption of paints and varnishes and in many respects determines the required thickness of the operational-capable coatings. For example, the expenditure coefficients of paints when applied to wood are 2-3 times higher than when applied to metals (non-porous materials). The thickness of the protective coatings must exceed the maximum height of the surface microroughness by at least 20%. In this regard, there is an acceptable roughness limit - an acceptable surface is at least 4 purity classes ($R_a = 10$ μm; $R_z = 40$ μm). The norm of steel roughness after shot blasting is R_{max} = 55 - 85 μm. It must be borne in mind that even at values of $R_{max} > 3$ μm and $R_a > 0.5$ μm, the surface roughness of the substrate manifests itself in the coating and the larger the thinner the film. Creating a given relief and controlling the degree of surface roughness is carried out in various ways: mechanical, chemical, thermal, electrochemical processing, etc. [15].

The surface roughness affects, in particular, the adhesion of dust particles to surfaces made of various building materials. To this end, Zimon A.D. investigated the adhesion of smooth spherical glass particles to a rough surface. As a rough surface, steel surfaces treated according to various purity classes were used [10]. Figure 1 [10] shows the change in adhesion numbers (γ_F – is the value equal to the ratio of the number of particles remaining on the surface after exposure to tearing force to the number of particles initially on the surface [8–11]) depending on the cleanliness class of processing steel surfaces for glass spherical particles with different tearing forces. As can be seen from the above data, the adhesion numbers, and therefore the adhesion itself, reach maximum values for steel plates processed according to grade 13. With a deterioration in processing quality to grade 10, the adhesion numbers decrease and then increase again. The roughness of the substrate practically does not affect the adhesion numbers of small particles with a small removal force (curve 1, Figure 1) and large particles (diameter 70 μm) with a significant removal force (curve 3', Figure 1). In the first case, almost all particles are held on the surface, in the second, almost all particles are removed. Thus, surface roughness does not affect adhesion for the two extreme points of the integral adhesion force curves [10].

Based on the data obtained, three cases can be distinguished that characterize the effect of surface roughness on the adhesion of glass spherical particles to steel surfaces. The first case is possible provided that the contacting surfaces are ideally smooth, for example, when glass spherical particles adhere to a melted glass surface or to metal surfaces treated in grade 13. The second case is possible when the height of the protrusions is less than the size of the particles. In this case, the area of the true contact of the particles with the surface decreases, and, therefore, the adhesion forces decrease. In the third case, an increase in adhesion forces occurs due to surface roughness, when the size of the protrusions is comparable with the size of the dust particles [10]. Analysis of these studies showed that adhesion on a microrough surface is less than on smooth or on surfaces with macro roughness [10]. However, these studies are applicable exclusively for the adhesion of smooth spherical glass particles to a steel surface. The process of adhesion of the atmospheric aerosol of urban environments (AAUE) on the vertical surfaces of buildings and structures is not well studied.

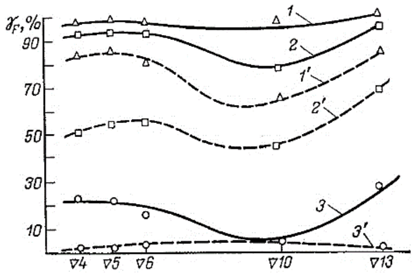

Figure 1. The dependence of the adhesion numbers of glass spherical particles of various sizes (1,1' – 20 μm, 2, 2' – 40 μm, 3,3' – 70 μm) to steel surfaces of different surface finish with a breaking strength of 70 units. g (1,2,3) and 1150 units. g (1',2',3')

The authors studied the process of AAUE adhesion on the most typical types of urban surfaces of vertical surfaces made of various building materials: glass, metal (steel), plastered, painted. We obtain the following options for the influence of roughness of a vertical surface on the adhesion of AAUE:

1) Upon contact of the AAUE with a glass vertical surface, processed according to the highest class of purity, i.e. with a smooth vertical surface (Figure 2, a).

2) Upon contact of the AAUE with metal, plastered and painted with vertical surfaces, processed not less than 10 class of surface cleanliness (Figure 2, b).

3) Upon contact of AAUE with metal, plastered and painted with vertical surfaces, processed below grade 10 surface cleanliness (Figure 2, c).

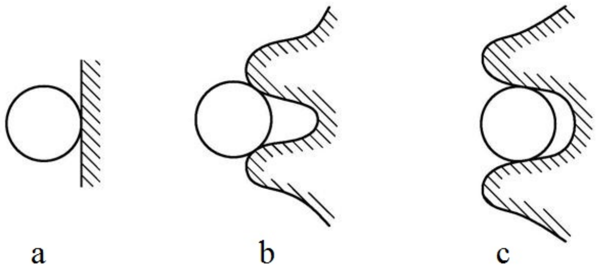

Figure 2. Effects of the roughness of the vertical surface on the adhesion of AAUE: a – contact with a smooth surface; b – the height of the protrusions of the surface is less than the particle size; c – the height of the surface protrusions is larger than the particle size

2.2 The influence of climatic factors on the adhesion of particulate matter on building materials

Climatic factors are the prevailing meteorological conditions for a given area that affect human body, animals, plants, as well as other environmental objects. Let's consider the main ones, namely, the temperature regime of atmospheric air, atmospheric humidity, atmospheric pressure; wind speed and direction, etc.

1) The temperature of atmospheric air is one of the most important characteristics of weather and climate, which has a direct effect on the state of man, animals, plants, on the operation of mechanisms, etc. It varies over time, both with height and in the horizontal direction over a wide range. Temperature changes cause fluctuations in atmospheric pressure. A higher daytime temperature near the surface of the earth helps to raise the air masses up and leads to additional turbulence. At night, the temperature at the surface of the earth decreases, therefore, turbulence decreases. The ability of the earth's surface to radiate or absorb heat leads to temperature inversion. An increase in air temperature with altitude leads to the fact that harmful emissions do not rise above a certain level. Under inversion conditions, turbulent exchange is weakened, the conditions for dispersion of harmful emissions in the surface layer of the atmosphere are getting worse. Figure 3 [10] shows the dependence of the adhesion number on the ambient temperature.

With the separation of particles with a diameter of 30 μm by the pulsed method, when the whole process is carried out at the same temperature, curve 3 is obtained. Curves 1, 2 are obtained by determining the adhesion by centrifugation. In the pulsed method, the influence of air humidity is excluded, therefore, the increase in adhesion forces with increasing ambient temperature can be explained by the ongoing change in the properties of the contacting bodies. An increase in the adhesion forces on painted surfaces (curves 2,3, Figure 3) can be explained by the appearance of coating stickiness, which increases with increasing temperature [10]. It was experimentally established that when a sample dusted in air (temperature 20 ° C and air humidity 50–60%) is placed in a medium with a low temperature (below 0°C), the adhesion forces sharply increase due to the "freezing" of particles to the surface due to condensation of moisture between the contacting bodies. But in the event that the surface dusting itself is carried out at a low temperature, the adhesion forces will not increase [10].

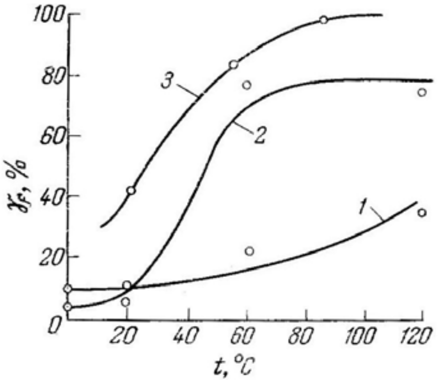

Figure 3. The dependence of the adhesion number on the ambient temperature of the glass particles to the following types of surfaces: 1 – to the glass surface; 2, 3 – to the surface painted with perchlorovinyl enamel

2) Humidity is the content of water vapor in the air, characterized by absolute humidity, specific humidity, relative humidity, moisture deficiency, dew point. Absolute humidity is the content in the atmosphere of water vapor in grams per 1 m^3 of air. Relative humidity is the ratio of the actual elasticity of water vapor to the elasticity of saturation, expressed as a percentage. Relative humidity characterizes the degree of saturation of air with water vapor. [17].

Figure 4 [10] shows the experimental values of the adhesion numbers of glass spherical particles to a glass plate, depending on the relative humidity of the air surrounding the dusty substrate. As can be seen from Figure 4, the modification, i.e. methylation with dimethyldichlorosilane of one of the contacting surfaces leads to a decrease in adhesion (curves 2, 3, Figure 4). Methylation of two contacting surfaces (curve 4, Figure 4) further reduces the adhesion forces [10].

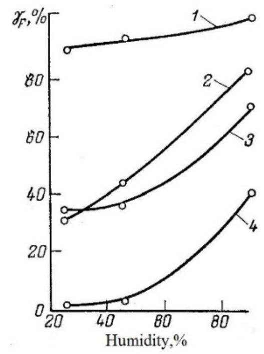

Figure 4. Dependence of the adhesion number on air humidity of glass spherical particles with a diameter of 70 ± 2 μm to a glass surface: 1 – ordinary glass; 2 – hydrophobic substrate; 3 – hydrophobic particles; 4 – hydrophobic particles and the substrate

3) Wind speed and direction. The main parameter affecting the distribution of pollutants in the atmosphere is the wind - this is the movement of air above the Earth's surface in the horizontal direction. Wind is characterized by speed, strength and direction [17]. There is a pattern in that the greater the wind speed, the greater the turbulence and, therefore, the faster the dispersion of atmospheric pollution. Investigations of the patterns of the distribution of atmospheric impurities and the peculiarities of their spatial and temporal distribution [18] are of great importance on atmospheric pollution, depending on meteorological factors. These patterns are an important component of an objective assessment of the state of the air basin and trends in pollution, and also make it possible to develop measures to ensure a clean atmosphere [17].

In the works of Zimon A.D., Deryagin B.V., Krotova N.A. and other scientists assessing the influence of climatic factors on the process of adhesion of particulate matter [19–23] speaks of the effect of air humidity on dust adhesion at values above 65%, as well as the small effect of air temperature on the process of adhesion of particulate matter. It should be noted the effect of "freezing" of particles to the surface, which occurs when a sample dusty at a positive temperature is placed in a medium with an air temperature below zero, because this is due to moisture condensation between the contacting bodies [10]. Since studies of the adhesion of solid particles on vertical surfaces made of various building materials were carried out in the conditions of the city of Volgograd, then, on the basis of many years of analysis of statistical data on changes in air humidity, it was found that the average annual values of this value do not exceed 65%. Based on the foregoing, the speed and direction of the air flow were selected as the determining climatic factors.

2.3 The experimental studies of particulate matter adhesion on the vertical surfaces made of various building materials

In order to study the patterns of pollution of buildings and structures, we conducted experimental studies of the process of adhesion of particulate matter on vertical surfaces, which are made of various building materials. Particle contamination of buildings consists of such components of the adhesion process as "particle sticking" and "particle removal" – processes that occur in certain directions of the air flow to a vertical surface, contributing to either dust particles sticking to the surface or removing them (blowing-off) from it [24,25]. The authors developed an installation for dusting vertical surfaces made of various building and finishing materials, the most characteristic of the urban environment (Figure 5). As the studied vertical surfaces, such samples as glass, steel, plastered, painted surfaces and other building and finishing materials were studied [26,27]. Thus, when conducting experimental studies on the sticking of particulate matter to the surface, the mass fraction of sticking urban dust particles to the vertical surface γ_{Fmass} was chosen as a response function, while in experimental studies on the removal of particulate matter from surfaces – the mass fraction of city dust particles that come off from the vertical surface, under the influence of wind per unit time: γA_{mass}. The plan of the full factorial experiment, which is a planning matrix corresponding to the central composite rototable plan, has been implemented. The experimental data were processed using the STATISTICA application software package.

1) Experimental studies of sticking of AAUE on vertical surfaces. Regression dependences were obtained for AAUE sticking to various vertical surfaces from four ecological and climatic factors: concentration of particulate matter (dust) in air flow *C*, μm/m^3; maximum size of particles *d*, μm; air flow speed *V*, m/s; airflow direction to a vertical surface (cosine of the airflow angle to a vertical surface), *φ*. For factors, the following intervals and levels of variation were established (Table 1) [24].

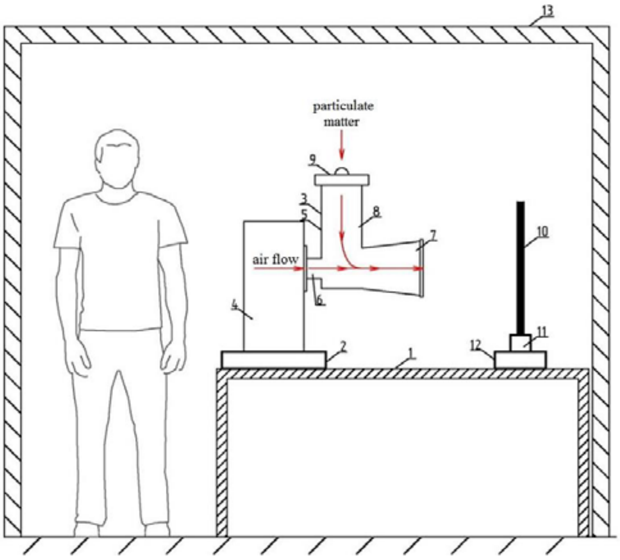

Figure 5. Installation for dusting a vertical plate: 1 – stand; 2 – rotary platform; 3 – device for dusting the plate; 4 – compressor; 5 – dust chamber; 6 – nozzle of air flow coming from compressor 4; 7 – diffuser; 8 – nozzle for supplying 5 dust sample to the dust-air chamber 5; 9 – cover; 10 – investigated vertical surface (plate); 11,12 – fastenings of plate 10 to stand 1; 13 – dustproof enclosing structure

Table 1. The source data for the design of the experiment

Factors	Varying intervals	Levels of variation		
		-1	0	+1
Concentration of particulate matter (dust) in air flow *C*, μm/m^3	0,5	0,5	1	1,5
Maximum size of particles *d*, μm	10	10	20	30
Air flow speed *V*, m/s	2,5	1	3,5	6
Air flow direction to a vertical surface, *φ*	0,3536	0,7071	0,3536	0

a) The studied sample of the vertical surface – *glass surface*. Under the glass surface in the work is meant a surface treated in the highest class of cleanliness, i.e. smooth vertical surface [18]:

$$\gamma_{F_{mass.glass}} = 0{,}00235 - 0{,}00589C - 0{,}0002988d + 0{,}00087V + 0{,}0055\varphi + 0{,}003992C^2 + 0{,}00000998d^2 \quad (1)$$

b) The studied samples of the vertical surface – plastered and painted surfaces. The plastered surface in the work is understood to mean a vertical surface finished with mineral plaster and corresponding to a surface cleanliness class of 10 or lower. Under the painted surface, a vertical surface painted with perchlorovinyl facade paint for exterior work and corresponding to a surface cleanliness class of 10 or lower is accepted in the work [18]:

$$\gamma_{F_{mass.p.}} = -0{,}00472 + 0{,}002432C + 0{,}0001104d + 0{,}001114V + 0{,}006667\varphi \quad (2)$$

c) The studied sample of the vertical surface – metal (steel) surface. Under the metal (steel) surface in the work is meant a vertical surface processed in accordance with the 10th class of surface cleanliness or lower [18]:

$$\gamma_{F_{mass.metal}} = -0{,}002737 + 0{,}00195C - 0{,}00024d + 0{,}0005V - 0{,}000319\varphi + 0{,}000009d^2 + 0{,}00078V \cdot \varphi + 0{,}0001589d \cdot \varphi \quad (3)$$

2) Experimental studies of the removal of urban dust particles from vertical surfaces. In our opinion, in addition to the previously studied climatic factors (speed and direction of the air flow), the size of the dust layer that had previously adhered to the surface is important. Regression dependences were obtained for the removal of dust particles from various vertical surfaces from three random factors: the density of dust sticking to vertical surfaces G, mg/m^2; air flow speed V, m/s; airflow direction to a vertical surface (cosine of the airflow angle to a vertical surface), φ. For the factors, the following intervals and levels of variation were established (Table 2). Negative values of the regression coefficients are conventionally used to illustrate the process of removal (blowing-off) of particles from the surface [24].

Table 2. The source data for the design of the experiment

Factors	Varying intervals	Levels of variation		
		-1	0	+1
Density of dust sticking to vertical surfaces G, mg/m^2	20	3	23	43
Air flow speed V, m/s	2,5	1	3,5	6
Air flow direction to a vertical surface, φ	0,3536	0,9397	0,9848	1

a) The studied samples of the vertical surface – plastered and painted surfaces:

$$\gamma A_{mass.p.} = -0{,}99527 - 0{,}00007G + 0{,}00108V - 0{,}00378\varphi + 0{,}00033G \cdot \varphi - 0{,}001086V \cdot \varphi \quad (4)$$

b) The studied sample of the vertical surface – glass surface:

$$\gamma A_{mass.glass} = -0{,}99499 + 0{,}00012G + 0{,}000005V - 0{,}0074\varphi + 0{,}000005G^2 + 0{,}00376\varphi^2 \quad (5)$$

c) The studied sample of the vertical surface – metal (steel) surface:

$$\gamma A_{mass.metal} = -0{,}99837 + 0{,}00013G + 0{,}000005G^2 \quad (6)$$

The adequacy of mathematical models was determined by the Fisher criterion, the significance of the calculated regression coefficients for the sticking and removing of urban dust particles on vertical surfaces from random factors was determined by the Student criterion.

3. Results and discussion

Based on the results of experimental studies, it was found that in both experiments, the speed and direction of the air flow to a vertical surface are the most significant. However, during the process of the removal of dust particles from vertical surfaces, in addition to these factors, the sticking density is of particular importance (the value of the previously adhering dust layer on vertical surfaces G, mg/m^2).

It has been experimentally proved that dusting of vertical surfaces is carried out in the "zone of stable sticking" with a "positive" direction of air flow to a vertical surface in the range of 30° ÷ 150°. The maximum values of sticking are achieved when the air flow is directed to a vertical surface at an angle of 90° (Figure 6).

The process of the removal of particles from vertical surfaces is carried out in the "zones of stable removal" with "negative" directions of the air flow to the vertical surface in the ranges 0 ÷ 20° and 160° ÷ 180°. The maximum values of removal of urban dust particles – with the direction of air flow along a vertical surface (Figure 6). When the values of the air flow directions to the vertical surface are in the ranges of 20° ÷ 30° and 150° ÷ 160°, which are called "transition zones", partial sticking and removal of dust particles occurs: ranges 25° ÷ 30° and 150° ÷ 155° are “zones of unstable sticking”, where particles mainly stick to the surface, the ranges 20° ÷ 25° and 155° ÷ 160° are “zones of unstable removal”, where particles mainly come off the surface (Figure 6). However, under certain regimes of air flow rates to a vertical surface, insignificant removal of dust particles in the "zone of unstable sticking" and insignificant sticking of dust in the "zone of unstable removal" on vertical surfaces of buildings is allowed.

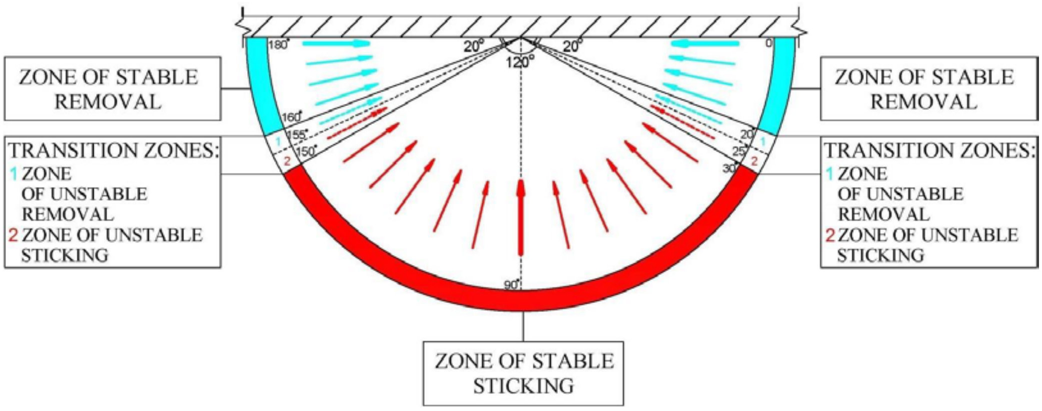

Figure 6. Investigated air flow directions to a vertical surface

4. Conclusions

1) The existence of the air flow directions to the vertical surfaces of buildings and structures, which particles of atmospheric aerosol of urban environment (AAUE) sticking, and directions of air flow which particles are removed, is experimentally established and then confirmed by the field studies.

2) The experimental installation for dusting vertical surfaces has been developed. It allows to study the patterns of the adhesion of particulate matter on vertical surfaces made of various building and finishing materials under laboratory conditions for various air flow conditions.

3) The regression dependences of the mass fraction of sticking of AAUE on vertical surfaces, as well as the regression dependences of the mass fraction of dust particle removal from vertical surfaces most characteristic of the urban environment (glass, metal, plastered, painted), from random factors: dust concentration in atmospheric air, maximum particle size, air flow speed, air flow direction to a vertical surface and sticking density were received.

4) It was established that when studying the process of adhesion of particulate matter on various vertical surfaces in the conditions of Volgograd, the most significant of the studied factors are the speed and the direction of air flow, and also when the particles are removed, the particle sticking density is of particular importance (the size of the previously sticking dust layer on vertical surfaces).

5) Based on the regression dependences, as well as field studies, it was found that the largest amount of particulate matter for the annual observation period was recorded on a glass vertical surface. The size of the dust layer on this surface exceeds similar values by 15% on plastered and painted surfaces, as well as 60% on a metal surface.

This data is explained by the features of the adhesion of particulate matter on surfaces: adhesion on a microrough surface is less than on smooth or on macrorough surfaces, as well as the electrical properties of glass.

5. References

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