Theory and Building Practice
Vol. 8, No. 2, 2005

https://doi.org/10.23939/jtbp2025.02.

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SOME FEATURES OF THE INFLUENCE OF FLAKED PARTICLES ON THE STRUCTURE FORMATION OF CONCRETE

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In the article, based on the literature analysis, it was shown that the particle shape, size, quantity, and ratio between the fractions of coarse aggregate affect the workability of concrete mixtures, as well as the density, strength, and durability of concrete. This applies to all types of concrete mixtures, from self-compacting (SCC) to rigid (RCC). However, studies mainly focus on cube-shaped aggregates, while crushed ones, which has a flake-like shape, is widely used in concrete. In Ukraine, quartzite crushed stone with 25–55 % flake particles are used in pavement concrete. It was found that flake particles significantly influence structure formation in concrete. If they are positioned horizontally during compaction, large air voids may form underneath, followed by smaller bubbles. This weakens the contact zone, reducing concrete density, flexural strength, and durability while increasing water absorption.

Keywords: flaky particles, coarse aggregate, grain shape, structure formation, air pores, strength.

Introduction

It is known that coarse aggregate and its quality are the main factors that have a significant impact on the properties of all types of heavy-weight cement concrete, including self-compacting mixtures (SCC). Mainly, this applies to such indicators as the maximum aggregate size, texture, genesis and shape of coarse aggregate grains. The article (Khaleel, 2011) presents the results of a study of SCC on crushed gravel, natural gravel and crushed limestone. It was shown that concrete mixtures containing crushed limestone have higher strength and elastic modulus than mixtures prepared on crushed and natural gravel. At the same time, the strength of SCC containing fine aggregate is higher than that of SCC based on coarse one.

Studies have shown that the properties of SCC are greatly influenced by the parameters of aggregates, primarily coarse aggregate. These include shape, texture, structure, maximum grain size, and granulometric composition of aggregate mix. The shape and size of coarse aggregate have a major impact on the mortar volume and the volume of cement paste which are necessary to coat all aggregate particles. The smallest volumes of cement mortar and cement paste correspond to particles with a smooth surface and flat (actually flaky) shape. Therefore, natural gravel requires significantly less mortar or paste than, for example, crushed gravel or crushed limestone, the shape of which is close to cubic. In addition, crushed aggregate significantly reduces the flowability of concrete mixtures due to the mechanical interlocking of angular particles. At the same time, smooth and flat aggregate improves the flowability of mixtures due to lower internal friction.

It is noted that the most important point in the effective application of SCC is the use of fractionated filler. If poorly fractionated filler is used, then the problem of increasing the viscosity of the mixture and segregation of the filler appears. In addition, it is necessary to reduce the maximum grain size in SCC because the permeability of cast concrete mixtures in densely reinforced structures is sharply reduced.

The necessary optimization of the amount of coarse aggregate includes two indicators: a decrease in the maximum size of the aggregate, for example, to 10–20 mm, which allows increasing the amount of coarse aggregate in SCC; the shape of the grains, which, ideally, should tend to be rounded, which will also allow increasing the content of coarse aggregate.

Studies have shown that the compressive and flexural strength, as well as the modulus of elasticity of concrete with D_{max} = 10 mm are higher than these indicators for concrete with D_{max} = 20 mm. According to the authors of the article, this can be explained by the fact that with a smaller particle size, their total contact area increases, and, therefore, the role of the transition zone (TZ) and the contact zone “aggregate-hardened cement paste” increases, which will make an additional contribution to the strength and durability of concrete.

It should be noted that, despite the fact that there are no descriptions of studies of the properties of concretes containing flaky particles in the world literature, the shape of natural gravel particles is very similar to these particles. Therefore, it is logical to assume that the technological and structural problems which arise in the manufacturing of concretes which contains flaky particles are similar to the problems of concretes on natural gravel. The main indicator of the durability of concrete is its freeze-thaw resistance, and for pavment concrete – the resistance of concrete to the simultaneous action of alternating freezing and thawing and salt solutions aggresion. In the work (Zarauskas, 2017) it is shown that the freeze-thaw resistance of concrete can be regulated by changing the content of coarse aggregate in the concrete mix, since this changes the porosity of the concrete. For example, it is assumed that with an increase of the volume of coarse aggregate, the predicted freeze-thaw resistance of concrete decreases. This is confirmed by the studies of D. Nagrockienė, which showed that concrete with a large amount of coarse aggregate has low closed porosity and therefore low freeze-thaw resistance (Nagrockienė, 2011).

It is worth noting that in terms of ensuring the minimum surface area of the aggregate mix, concrete mixtures should contain the maximum amount of coarse aggregate. In this case, the role of the grain shape increases, which affects the properties of fresh and hardened concrete. Therefore, the opinions of different scientists regarding the amount of coarse aggregate in concrete are different. Research by G. Skripkiunas showed that the main attention when creating strong and durable concrete should be paid to the uniform distribution of coarse aggregates in the volume of concrete and reducing the concentration of stresses in the contact zone around them (Skripkiunas, 2001). The results of these studies show that with an increase in the volume occupied by coarse aggregate, the water absorption of concrete decreases. At the same time, the rate of water absorption in the first hour is 86 % in concrete on natural gravel and 72 % in concrete on crushed gravel from the total water absorption. Moreover, when using crushed gravel, the total porosity of concrete increases compared to concretes containing natural gravel. The same studies showed that the shape of the coarse aggregate particles does not have a significant effect on the amount of air in the concrete mixture and the freeze-thaw resistance of concrete. The possibility of controlling the properties of concrete by optimizing porosity, primarily open porosity, is shown in (Butakova, 2017). Such optimization can be most easily carried out by ensuring a rational granulometric composition of coarse aggregates.

The grain shape and surface properties of the aggregate largely determine the water consumption for concrete mix (Yamei, 2017). For example, the larger the surface area of the coarse aggregate, the more water is needed to achieve desired workability. At the same time, angular particles increase the compressive and bending strength of concrete. According to the authors, such particles contribute to an increase of water consumption for concrete mixes but reduce the amount of entrained air. Accordingly, flat and smooth particles can contribute to an increase in air entrainment.

It is known that corrosion resistance, freeze-thaw resistance and permeability of concrete in different environments depend on the distribution of pores in concrete (Zhang, 2020). By changing the structure of pores, it is possible to control the durability of concrete, which can be increased by reducing the size of pores, primarily in the mortar part of the concrete, and ensuring their uniform distribution in the volume of concrete (Li, 2021).

One option for changing the pore structure is to control the granulometric composition of coarse aggregates. When preparing the concrete mix, large aggregate particles destroy large air bubbles and thus make the pore structure more uniform.

The maximum size of aggregate particles has a significant effect on many properties of concrete. As the particle size increases, the heterogeneity of the aggregate mixture increases (Wang, 2024) and the heterogeneity of concrete increases as well. A positive effect of increasing the content of coarse aggregate in concrete and its maximum size is an increase of the compressive strength of concrete, especially at high loading rates.

A relationship was established between the degree of homogeneity of the granulometry of coarse aggregate and the mechanism of concrete failure (Gimenes, 2023; Grassl, 2023). In these studies, it was found that the strength of concrete is affected by granulometry, grain shape and content of coarse aggregate. With an increase of the size and amount of aggregate, the flexural strength of concrete also increases. The mechanism of this phenomenon is explained by the fact that when using fractionated aggregate, small fractions of coarse aggregate lead to the formation of a greater number of contact zones, which leads to a decrease in strength.

Studies conducted on concretes made of zero-slump mixtures, in particular Roller Compacted Concrete (RCC), have shown that the physical and mechanical properties of RCC, as well as the properties of SCC, largely depend on the quality of the coarse aggregate and its granulometric composition (Almajeed, 2024). It is known that RCC has reduced water and cement consumption, but an increased amount of fine aggregate, which fills the voids between coarse aggregate. However, the abrasion resistance of RCC increases with increasing concrete strength and the amount of coarse aggregate in its composition. At the same time, the effect of the aggregate content on the abrasion resistance of concrete is significantly higher than the effect of cement consumption. The uniformity of the granulometric composition of the aggregates and its continuity play an important role.

A reasonable ratio of fractions in coarse aggregates was established: very large 25 %, large 30 %, medium 25 % and small 20 % of the total mass (Shi, 2024). With such ratio of large particles in large aggregate, the density of compacted concrete is maximum, and the number of roller passes is minimal. At the same time, in contrast to the SCC composition, to reduce the segregation of large aggregate particles it is necessary to limit the maximum particle size and the proportion of large aggregate. However, it was suggested that with an increase of D_{max} of the aggregate, its voidness may decrease, although this contradicts the results of other authors.

Segregation can be a significant problem for RCC if the granulometry of the coarse aggregate is not uniform and the particle size is high (Zhang, 2020). Segregation has also been shown to decrease with the square of the particle radius.

It is also interesting that if the ratio between the fractions of coarse aggregate is chosen poorly, a rigid, practically incompressible framework of aggregate grains can form, which cannot be compacted by rolling (Khasanov, 2021).

An analysis of the literature allows us to say that, even though many scientists point to the influence of the shape of large aggregate on the properties of concrete mixtures of different workability and concretes based on them, there are no studies on the influence of flat particles. In addition, it should be noted that not all quarries of stone materials in Ukraine produce aggregate in which the amount of flaky particles is less than 15 %. Firstly, this applies to quarries where quartzites are mined and processed. The number of flaky particles in quartzites can reach 55 %, depending on the crushing equipment used (Tolmachov, 2024). In addition, the shape of natural gravel particles is also similar to flat particles.

Therefore, the purpose of this article is to study the influence of flat particles in large aggregate on the properties of concrete mixtures and concretes.

Materials and methods of research

Granite macadam of 5–10 mm and 10–20 mm fractions with different contents of flake particles were used in the experiments. The control concrete composition used macadam containing 5 % of flake particles. In other compositions, the content of flake particles in the macadam was artificially increased. Portland cement of the Ivano-Frankivsk plant CEM I-42.5N and quartz sand with a fineness modulus Fm = 1.9 were also used in the experiments. Since the main aim of the studies was to establish the effect of flake particles on the properties of concrete mixtures and concrete, additives were not introduced into the concrete compositions. The studies were carried out on beam samples measuring 40×40×160 mm, as well as on beam samples measuring 70.7×70.7×280 mm. Before testing, the samples were allowed to harden under normal conditions for 28 days, after which they were tested for compressive and bending strength in accordance with the standards adopted in Ukraine.

Results and discussion

It is known that the pore structure of concrete affects many of its properties. For example, large pores reduce the strength of concrete, increase its permeability and abrasion. Micropores increase the corrosion resistance of concrete and its frost resistance. However, if the pores are concentrated in one specific place in the concrete structure, then the destruction of the concrete will begin in this place. In the studies of other scientists it was shown that there is a risk of voids forming under flat particles of large aggregate (Yu, 2015; Molugaram, 2014), as shown in Fig. 1. However, these works dealt with macro voids. But studies that would show the nature of the distribution of pores under particles of different shapes have not been conducted.

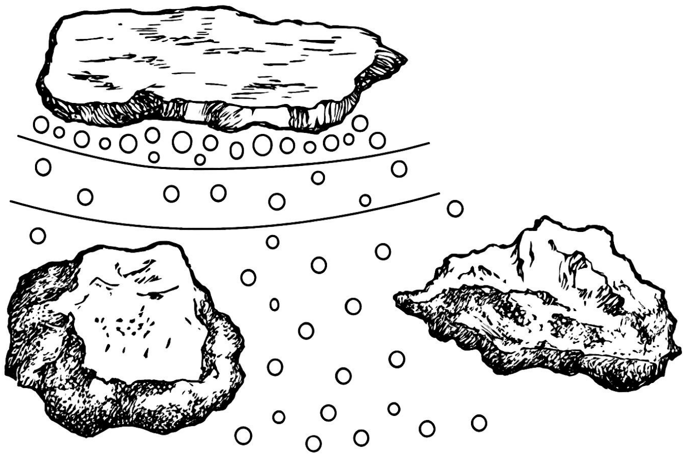


Fig. 1. Diagram of porosity between coarse particles (according to [19])
1 – pore zone under the flaky particle; 2 – pore zone in the mortar part of the concrete;
3 – pore zone between the cuboid particles

The arrangement of pores in the volume of concrete was shown in (Zakharov, 2019). The main idea of such an arrangement of pores is that for compaction of concrete mixture by vibration it is necessary that the frequency of the vibrator coincides with the natural frequency of oscillations of the large aggregate. In general, the frequencies coincide with cubic particles, but do not coincide with flake-shaped particles. As shown in the studies of B. Gusev, the optimal vibration frequency of the vibrator for compacting concrete mixtures should be at least 40 Hz (Gusev, 1991). At this frequency, mixtures with cubic particles are effectively compacted. The vibration amplitude should also be different for mixtures with cubic and flat particles. But this is impossible in production conditions. In addition, most concrete placers have vibrators with a high vibration frequency of 7000–12000 min^{-1} and low amplitude. These parameters are suitable for compaction of flowing concrete mixtures with cube-shaped coarse aggregate. It is logical to assume that flat particles, which have a larger surface area than cubic particles, will tend to rise to the surface of the mix being compacted under such vibration parameters. With such vibration and with a horizontal arrangement of flat particles, large air bubbles can form under their lower surface. Further, under the action of vibration, the destruction and dispersion of large air bubbles will occur. In this case, many small pores will form under the flat particle, the number of which is greater than in the mortar part of the concrete and under the cubic particles. This will lead to the formation of a zone of high porosity, which will not be compacted, but will be a weak link in the concrete structure.

Beam samples measuring 70.7×70.7×280 mm were made of concrete of one strength class (C30/35). The content of flat particles in the coarse aggregate varied in their compositions. After 28 days of hardening, the samples were cut vertically and the number of flat particles in each section was determined. A total of 6 sections were made for each concrete composition. The studies showed that flat particles are able to rise to the surface of the sample when compacted by vibration (Table 1). It was found that with a small number of flat particles (5 % of the total mass of crushed stone), they are distributed evenly along the height of the concrete. But if the number of flat particles increases, then during vibration they rise to the upper part of the sample, and their number in the upper part increases. These studies showed that with such vibration, flat particles of macadam behave like a lightweight filler.

Table 1

Number of flaky particles by height of concrete sample

The amount of flake particles in aggregate, % by weight	Number of flake particles in the cross-section of a concrete sample, pieces	
	Upper part	Bottom part
5	3	4
15	9	4
25	12	6

In production conditions, high-frequency vibration with a small oscillation amplitude is most often used, which facilitates the compaction of concrete mixtures with cubic-shaped macadam. For mixtures with a large number of flake particles, low-frequency vibration is required, but with a large amplitude, which, according to the research of B. Gusev, must be used to compact concrete mixtures on lightweight aggregates (Gusev, 1991). The amount of flaky particles in aggregate for pavement was previously limited to 25%, and is currently 15 % as a requirement of DSTU 8858:2019. However, there is no data in the literature on the effect of such an amount of flaky particles on the properties of concrete.

The flexural strength of concrete decreases by 8 % with an increase of the amount of flake particles to 10 % (Table 2). This indicator further decreased to a content of flake particles in aggregate at the level of 20 %. And then, as for the compressive strength, no decrease in the flexural strength was observed. The overall decrease in flexural strength is 15 %. Such a significant decrease in strength indicates the influence of flake particles on the contact zone of “hardened cement paste – aggregate” and the transition zone (TZ). Thus, the above mechanism is confirmed, according to which in the contact zone “flake particle – hardened cement paste”, is probably in the lower part of the particle, a zone is formed that is poorly compacted. This zone is a weak link in the mesostructure of concrete and is the reason for the decrease in its strength.

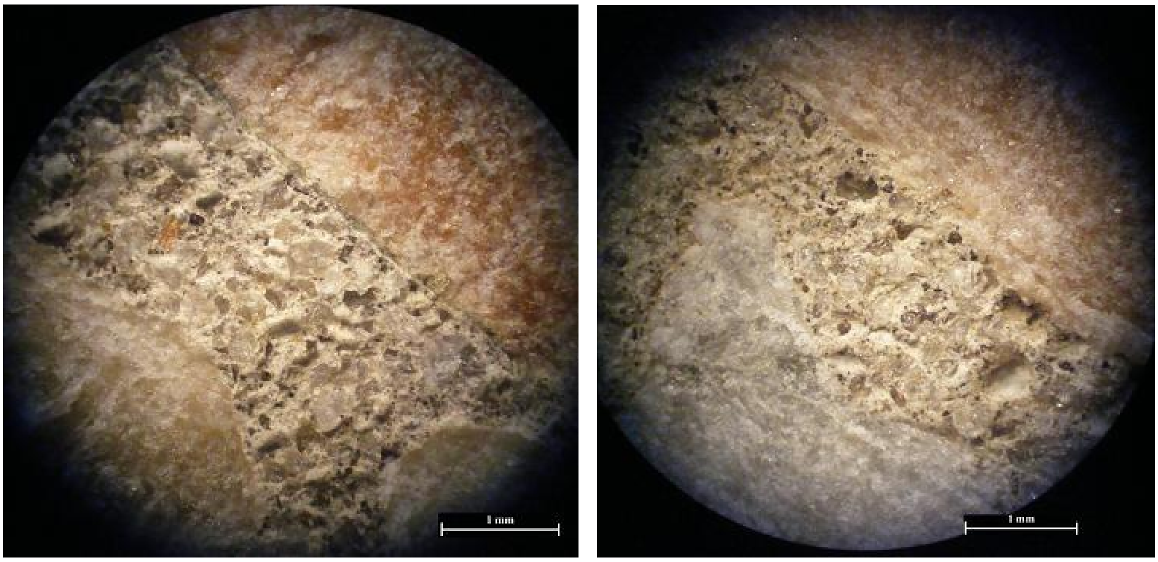
Table 2

The influence of flake particles on the strength of cement concrete

Strength, MPa	Quantity of flaky particles, wt. % of total aggregate				
	5	10	15	20	25
Compressive strength	58.3	56.4	55.6	55.6	55.6
Bending strength	9.52	8.85	8.55	8.25	8.25

The conducted studies have shown that with an increase of the amount of flaky particles in the composition of aggregate, the compressive strength of concrete decreases. However, with each increase in the amount of flakes by 5 %, the strength of concrete decreases insignificantly – by 1–3 %. When moving from 5 % of flake particles to 15 %, the decrease of strength is 5%. Further, the compressive strength of concrete does not decrease. Such a decrease of compressive strength is within the error limits of testing. This indicates that in the considered range of the content of flake particles, their influence does not affect the macrostructure of concrete.

The optical microscopic studies conducted showed that the structure of the contact zone and the transition zone depends on the amount of flake particles in the macadam (Fig. 2). As can be seen from the photographs presented, with a flake particle amount of 5 %, the contact zone "flake particle – hardened cement paste" can be clearly identified (Fig. 2, *a*). The contact zone is adjoined by a transition zone $2–3\times 10^{-4}$ m wide, in which pores of $0.8–1.2 \times 10^{-4}$ m can be seen. This indicates insufficient compaction of this zone due to the fact that the vibration parameters do not coincide with the natural vibration frequency of the flake particles.



a *b*

Fig. 2. Optical microscopic photograph of the contact zone
a – content of flake particles 5 %; b – content of flake particles 15 %

In the concrete sample containing 15 % of flake particles, a clear contact zone can also be seen, as well as a transition zone (Fig. 2, *b*). The transition zone is wider (up to $5–6\times10^{-4}$ m) than in the case where the content of flake particles is 5 %. The pores in this zone are also significantly larger and reach a diameter of $1.6–2.4\times10^{-4}$ m. Here, mesostructure defects with a diameter of 5×10^{-4} m can be seen. In the mortar part of the concrete, the number of pores is increased under the flake particle. This confirms that loose zones appear in the concrete under the flake particles, in which the mortar part is poorly compacted. Direct tests showed that the water absorption of concrete with different amounts of flake particles is different and increases with an increase in the number of these particles (Table 3).

Table 3

Water absorption of concrete samples with different amounts of flake particles

Sample form	Water absorption of concrete, *W*, %, with the number of flake particles		
	5 %	15 %	25 %
Cubes	1.76	2.4	3.0
Beams	2.0	2.8	3.6

It is obvious that the increase of the amount of flake particles in macadam leads to an increase in water absorption. If we take into account that water absorption is an indicator of the amount of open pores, then we can conclude that with an increase of the content of flake particles in macadam, the open porosity of concrete increases. These studies confirm the results of optical microscopic studies and the mechanism of the influence of flake particles on the formation of concrete structure and its properties.

Conclusions

1. It is shown that gravel and quartzite macadam are used for the production of heavy concrete for transport purposes, which may contain a high amount of flake particles that affect the properties of concrete mixtures and concrete.

2. It has been established that when compacting concrete mixtures by vibration with traditional parameters, flake particles can rise to the upper part of the concrete. At the same time, zones of increased porosity are formed under them.

3. Studies of the strength of concrete with different amounts of flake particles have shown that increasing their number does not change the compressive strength of concrete, but reduces the flexural strength of concrete.

4. It has been shown that an increase of the amount of flake particles in crushed stone leads to an increase in water absorption of concrete, primarily due to an increase of the number of open pores.

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ДЕЯКІ ОСОБЛИВОСТІ ВПЛИВУ ЛЕЩАДНИХ ЧАСТОК НА СТРУКТУРОУТВОРЕННЯ БЕТОНІВ

У статті розглянуто вплив лещадних зерен у складі грубого заповнювача на властивості важкого цементного бетону, призначеного для транспортного та промислового будівництва. Якість грубого заповнювача є одним із визначальних факторів, що формують структуру і довговічність бетону, особливо у разі використання щебеню з кварцитів і гранітів, для яких характерна підвищена кількість лещадних зерен. У роботі експериментально досліджено бетонні суміші, виготовлені на щебені фракцій 5–10 мм та 10–20 мм з різним вмістом лещадних зерен (від 5 до 25 %).

Встановлено, що під час ущільнення бетонних сумішей традиційною вібрацією лещадні зерна мають тенденцію до переміщення у верхні шари бетону, де під їхньою плоскою поверхнею формуються зони підвищеної пористості. Оптична мікроскопія показала, що зі збільшенням вмісту лещадних зерен ширина перехідної зони “зерно – цементний камінь” зростає майже вдвічі, а діаметр пор збільшується з $1{,}0\times10^{-4}$ до $2{,}4\times10^{-4}$ м. Такі мікроструктурні дефекти знижують міцність на згин та сприяють підвищенню водопоглинання.

Результати випробувань свідчать, що зі зростанням кількості лещадних зерен від 5 % до 25 % міцність на стиск практично не змінюється, проте міцність на згин зменшується на 10–15 %. Водопоглинання бетонів підвищується з 1,8 % до 3,6 %, що свідчить про збільшення відкритої пористості та можливе зниження морозостійкості. Отже, надлишковий вміст лещадних зерен у заповнювачі негативно впливає на структуру контактної зони та довговічність бетону.

Отримані результати мають практичне значення для оптимізації складу бетонів, виготовлених на місцевих заповнювачах, а також для розроблення рекомендацій щодо коригування параметрів віброущільнення бетонних сумішей із підвищеним вмістом лещадних зерен.

Ключові слова: лещадні частинки, грубий заповнювач, форма зерен, структуроутворення, повітряні пори, міцність.