Decorative light transmitting concrete based on crushed concrete fines

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Abstract. The increasing demand for decorative materials among architects and designers has led to the development of various new building materials. The combination of types of functional significance was the reason for the creation of light transmitting concretes (known as LiTraCon), which are combined the light-transmitting and constructive functions. Such concrete can be used in the decorative finishing of internal surfaces and the creation of decorative products. The most common technology for obtaining light transmitting concrete based on the process of introducing oriented light-conducting fibers into the concrete mixture. This technology is complex and labor-intensive, which leads to increased cost of the material. The usage of translucent compounds instead of light transmitting fibers can enhance the mechanical properties of the material. The polymer resins introduced in the composition at formation of material interact with concrete mix and form a dense contact zone between the layers of the solidified compound and concrete. Also, introduction of composition of mechanically and chemically activated crushed concrete fines and silica fume to the complex binder could lead to further decreasing of the cost of light transmitting concrete and to improve the process of hardening of concrete mix without loss of the physical properties. Developed light transmitting concrete works as two-layered system, both components of it has similar stress and bending strength, with a dense contact zone between layers. Aforementioned complex binder was chosen to form a concrete matrix and various types of acrylic-based and epoxy-based resins were chosen to form a translucent layer. To find out the influence of admixtures on the properties of light transmitting concrete, the experimental study of physical and mechanical properties and structure of the material were conducted. The influence of type and specific surface of crushed concrete fines and silica fume on the structure and quality of decorative surface was examined. The compressive strength of concrete and adhesion between layers of concrete and translucent compound were found using the standard testing methods. The structure of concrete was examined using the methods of electron microscopy and X-ray analysis. The study of the properties of concrete shows that developed material has a compressive strength of 30 Mpa, strong adhesion of layers (destruction of material due tests goes through the matrix of concrete) and sufficient light transmitting ability.

1. Introduction

Due to economic development and space utilization requirements, high-rise buildings and skyscrapers are mostly built downtown in metropolitan areas around the world, especially in countries with great populations. Those buildings have isolated biosphere based mostly on man-made lights to maintain
people’s optical activities. Hungarian architect Aron Losonczi first introduced the idea of light transmitting concrete in 2001 and then successfully produced the first transparent concrete block in 2003, named LiTraCon (Light Transmitting Concrete). Litracon is a combination of optical fibers and fine aggregate-based concrete. Litracon rooms will be brightened and proximal objects situated on the brighter side of a Litracon wall will be revealed as silhouettes on the other side. Though the optical fibers compose only 4% of the concrete, some light is transmitted because of their parallel arrangement in a matrix between to the two outer surfaces of each block. Load-bearing structures can also be built from these blocks, since glass fibers have almost no negative effect on the strength of the concrete. Still, there are some problems in usage of Litracon in mass construction.

As a construction material, Litracon has his advantages – it could have high decorative properties, resistance to compression loads (up to 50N/mm²) and bending (up to 7 N/mm²), blocks may have different forms and dimensions, it could be used to build several meters high walls, transfer light from outside without major changes (intensity of light, colour, etc.). Nevertheless, this type of material has a high cost (about 750 per square meter of 2.5 mm thick wall), cannot be made right on the construction site, not mention of the need of skilled personnel to made walls from it.

Most of the properties of Litracon appear from the type of light transmitting element – an optical fiber. The need to put the fiber into the cement matrix in a certain way and the need to polish the surface after the hardening of concrete are the main reasons of difficulty of production and high cost of ready product.

Nowadays, there are lot of studies devoted to the increasing of Litracon properties. There are different materials which could be used in formation of light transmitting component of the light transparent concrete, such as glass, translucent stone, etc. [1, 2]. Traditional optical polymer glass fiber is most commonly used in the technology.

The main idea of the research was the possibility of forming the light transmitting element in concrete matrix using transparent polymer resins. These resins are widely used in construction as components of composite materials, as glues etc. There is wide selection of such resins, for example, it could be epoxy resin or acrylic resin. Concrete matrix could be made using concrete made on fine aggregate only. Light transmitting element could be obtained by the technology of layered setup of the compound to achieve continuous layers which could effectively work in the material. Also, the usage of modern pigments and admixtures could allow to make a concrete with high decorative effect. This could solve the problem of high difficulty of the making process, but the cost of material could not be decreased that way.

One of solutions to decrease cost of production is to change components of the concrete mix to cheaper ones. The usage of recycled crushed concrete aggregate produced by crushing of concrete waste may not only reduce the consumption of natural aggregate, but may reduce the amount of concrete waste that ends up in landfills as well. The screening process at the screening plants produces coarse recycled concrete aggregate (with particle size more than 5 mm) and fine recycled concrete aggregate (with particle size less than 5 mm). There were a lot of studies of coarse recycled concrete aggregate and fine recycled concrete aggregate, which shows that these aggregates could be used as a replacement for natural aggregates in structural concrete. Various researchers [3-4] have proved that the use of crushed concrete of a fraction of 5-40 mm in reinforced concrete and concrete products (up to 30% of the mass of a coarse aggregate without any special preparations) is possible; the technologies for the use of this aggregate had been developed. A little less research has been conducted on the application of fine recycled concrete aggregate in structural concrete and high performance concrete. The questions of usage of crushed concrete fines as filler for fine grain concrete, aerated and foam concrete products as well as technological solutions for the production of paving tiles on crushed concrete aggregates were worked out. All of these types of industry waste have been studied for possibility of their usage in decorative concrete previously [5].

However, the dust fraction of recycled concrete aggregate (which has particle size less than 0.063 mm) considered unwelcome in concrete technology. The main reasons of this are high specific surface which leads to high water consumption and influence on water/cement ratio and, therefore, the
negative impact on strength of concrete. Hydration water accumulates in porous structure of dust fraction particles and increases the amount of capillary pores in solid concrete. The methods of lowering of influence of absorbed water are the constant interest of researchers [6].

To achieve dense concrete structure with a little number of capillary pores, negative effect of dust fraction could be compensated by usage of superplasticizer [7]. It could decrease the amount of water used to hydrate cement and, more important, the amount of water accumulated by porous structure of dust fraction. Thus, the usage of crushed concrete fines as fine aggregate in composition with polycarboxylate superplasticizers could allow to create concrete structures with strength and density compared with traditional concrete materials.

Besides low capillary porosity, decorative materials should also meet the specific requirements on the quality of the front surface of the windshield and to ensure the absence of snow accumulation on the surface of buildings. Traditional materials based on cement binder could not always meet these requirements, but their main disadvantage is the relatively low durability. This happens due to the presence of extensive network of capillary porosity, hairline cracks and other structural defects which are formed at the stage of manufacture and during the life cycle.

The decorative effect of decorative concrete products could be created in various ways [8]. The most preferred method in technology of colored waste-and-concrete-based products is the joint mechanical and chemical activation of crushed concrete fines together with a mixture of pigment and binder [9].

The main problem of such method is the difference between rheology of layers. Concrete and polymer resin has different density and could mix with each other. This prevents the creation of clear layer of light transmitting element on the borders by introducing particles of concrete into compound. On the other side, polymer resin could diffuse and introduce itself into hardening concrete, increasing the strength of contact zone between layers.

To solve this problem, the difference between rheological characteristics of the components could be decreased by using different aggregates in the concrete mix. It was proposed that the usage of crushed concrete fines instead of sand could not only make the rheology of concrete closer to polymer resin, but it will also make designed material more ecological friendly.

2. Methods and materials

To confirm the theoretical propositions, concrete mixes with mechanically activated admixture based on the screenings of crushed concrete had been developed. The composition of admixture includes polycarboxylate superplasticizer, silica fume, iron oxide pigment and crushed concrete fines dust fraction with an average grain size less than 0.063 mm. The design of concrete mixes was calculated according to high performance concrete design methods [10-15].

Before experiment, available admixtures for use with high-performance decorative concrete were analyzed. As light transmitting elements, different compositions based on epoxy resin and acrylic resin were chosen. As superplasticizers, three types of polycarboxylate superplasticizers (Neoplast, Polyplast SP HPC and Glenium 51) as well as traditional naphthalene sulphonyl plasticizer C-3 were chosen for experiment. Lanxess Bayferrox iron oxide pigment was chosen to obtain color characteristics. Crushed concrete fines were obtained from crushed concrete, generated as a result of demolition of load carrying structures of buildings. Crushed concrete fines fraction 0-5 mm with an average density of 2.1 g/cm\(^3\), bulk density of 1.3 g/cm\(^3\), porosity of 7%, void content of 38%, crushing capacity grade 400; portland cement M500 with a standard consistency of 27.5% and portland cement of the M400 with a standard consistency of 27%; sand with the fineness modulus 1.35 and the amount of the dust fraction (0-0,14 mm) of 5%; technical water – all these components were chosen as concrete components.

Concrete mixes were tested to evaluate their workability, freeze-thaw resistance and unit elongation during freezing and thawing, porosity and water absorption, compressive strength and water resistance. The samples of light transmitting concrete were made by layer-by-layer positioning
of concrete mix and polymer resin in liquid form and were tested to find out their strength at age of 7 and 28 days.

All of the properties were determined on the samples with dimensions of 10x10x10 cm according to EN and GOST codes and standards. The experiment was made on the equipment of Moscow State University of Civil Engineering.

Standard samples of designed concrete were tested according the GOST methodic to find out the strength, porosity and capillary suction process, as well as dilatometry studies of samples based on the mechanically activated coarse aggregates. The components were introduced in two stages: silica fume, crushed concrete fines dust fraction and pigment were added to the cement prior to mechanical and chemical activation, plasticizer was added to the mixing water. Mechanical and chemical activation was carried out using an activator with an annular working chamber. The main feature of this type of activation device is the collision type: the particles in the vortex are subjected to collision with a velocity ~80 m/s. Initial tests were carried out for concrete mixes based on non-activated coarse aggregate. Compositions of these mixes are shown in Table 1.

**Table 1. Mix design of high-performance decorative concrete**

| Mix design | B30  | B35  | B40  | B45  | B50  | B60  | B70  |
|------------|------|------|------|------|------|------|------|
| Binder/water ratio | 1.92 | 2.14 | 2.39 | 2.64 | 2.83 | 3.3  | 3.77 |
| Cement, kg/m³ | 383  | 428  | 478  | 529  | 565  | 660  | 754  |
| Volume concentration of cement in water-cement paste | 0.33 | 0.36 | 0.39 | 0.42 | 0.44 | 0.5  | 0.55 |
| Silica and crushed concrete fines dust fraction, kg/m³ | 112  | 102  | 94   | 77   | 73   | 32   | 0    |
| Cement after, kg/m³ | 271  | 326  | 384  | 452  | 492  | 628  | 754  |
| Absolute volume of aggregate | 664  | 651  | 636  | 621  | 609  | 584  | 557  |
| Coarse aggregate, kg/m³ | 868  | 851  | 832  | 812  | 796  | 763  | 728  |
| Fine aggregate, kg/m³ | 868  | 851  | 832  | 812  | 796  | 763  | 728  |
| Compressive strength, MPa | 38.6 | 44.9 | 51.4 | 58.8 | 64.3 | 77.1 | 90.0 |
| Porosity, % | 13.7 | 13.5 | 13.4 | 13.0 | 12.8 | 12.2 | 11.2 |

Initial tests have shown (Table 2), that the concrete mixes suit the requirements of compressive strength and workability, but they do not meet the requirements for high-performance concrete freeze-thaw resistance (it was less than 400 cycles).

**Table 2. Main properties of high-performance decorative concrete based on non-activated coarse aggregate**

| Mix design | Compressive strength R, MPa | Porosity, % | Coefficient of water absorption | Unit elongation εlim 10⁻⁵ cm |
|------------|-----------------------------|-------------|-------------------------------|-----------------------------|
| B40        | 51.4                        | 13.4        | 9.92                          | 10.2                        |
| B45        | 58.8                        | 13.2        | 9.0                           | 10.5                        |
| B50        | 64.3                        | 12.8        | 8.41                          | 10.4                        |
| B60        | 77.1                        | 12.2        | 7.84                          | 9.6                         |

To improve the properties of developed high-performance concrete, a method of pretreatment of coarse aggregate by complex admixture was used. This admixture consists of silica fume and polycarboxylate superplasticizer and added to the concrete mix in two steps. At first, part of the mixing water containing silica fume and polycarboxylate superplasticizer is premixed with the coarse aggregate in the mixer and then added to the remaining water and cement.

Concrete samples based on non-activated and activated coarse aggregate after 28 days of normal storage were tested to find out the structure of concrete and properties of their matrix-aggregate
contact zones. The samples were split apart and the concrete from concrete-aggregate contact zones was collected. After that, collected material was disintegrated to powder and examined by differential thermal analysis and X-ray diffraction analysis. The degree of hydration of cement was determined based on the degree of hydration of C3S. Concrete samples based on activated coarse aggregate were also tested to find out their compressive strength, workability and coefficient of absorption. The properties of high performance decorative concrete based on non-activated coarse aggregate are shown in Table 3.

Table 3. Main properties of high-performance decorative concrete based on activated coarse aggregate

| Mix design | Compressive strength R, MPa | Porosity, % | Coefficient of water absorption | Unit elongation $\varepsilon_{\text{lim}} \times 10^{-5}$ cm |
|------------|---------------------------|-------------|-------------------------------|----------------------------------|
| B40        | 66.8                      | 13.4        | 8.4                          | 8.1                              |
| B45        | 70.5                      | 13.2        | 7.56                         | 8.5                              |
| B50        | 77.8                      | 12.8        | 6.75                         | 8.3                              |
| B60        | 91.7                      | 12.2        | 6.42                         | 8.0                              |

The influence of atmospheric factors on coloristic characteristics of decorative concrete were examined in salt-spray chamber.

3. Results and discussion

Studies have shown that the compressive strength of concrete, obtained by a two-stage activation, increased by 19-23%; water absorption value decreased by 16-20%; and unit elongation of concrete samples during freezing and thawing decreased by 17-20%. All samples had W12 water resistance degree. It was also found that porosity of all samples was not more than 14%.

The results of X-ray diffraction analysis showed a higher amount of calcium carbonate in the concrete in the non-activated coarse aggregate. That could be connected with a loose structure of the contact zone. Analysing the results of the experiments it can be concluded that the complex admixture, distributed on the surface of the filler, is interacting with calcium hydroxide and alter the type, volume and number of the pores and helps filling the contact zone by cement hydration products.

X-ray diffraction analysis showed that the degree of hydration of the concrete samples on activated coarse aggregate filler was 84%, whereas the hydration degree of concrete on non-activated coarse aggregate was only 73%.

The particles of the investigated dust fractions are slightly different in size from the traditional filler and have a rather high specific surface area. The particle size of part of non-activated crushed concrete fines is comparable to the size of the cement particles and silica fume and could replace them in the creation of concrete structures. Mechanical and chemical activation makes it possible to average these dimensions and to obtain high homogeneity of the activated admixtures based on crushed concrete dust fractions. The effect of mechanical and chemical activation allows to slightly reduce average size of particle depending of time of activation. The development of specific surface area of activated crushed concrete fines ensures strong adhesion between grains of binder and filler during the formation of cement stone matrix. The particle size distribution of the crushed concrete fines could achieve the densest structure of cement stone matrix and improve its resistance to environmental effects.

The main task of creating decorative concrete is the creation of high-quality surface that has highly decorative properties, persistent over time. The last property ensures high resistances to destructive surface environmental factors – freeze-thaw resistance, colour fade resistance, resistance to acids and alkalis and water-resistance. The most significant factor in these properties is the content of the concrete pores, especially capillary pores. The appearance of chipping, bleaching and discoloration at water saturation dramatically reduce the attractiveness of the product. To overcome the aforementioned defects of the front surface, it is necessary to increase the density of the concrete, and thereby increase its compressive strength [16]. One of the effective ways to solve this problem is the
Impregnation of high-performance decorative concrete by low viscosity concrete formulations which can be cured in the concrete pores. Such compounds are widely distributed, but they can affect the colour characteristics and general attractiveness.

The examined concrete mixes have a higher density and a smaller number of capillary pores. The high specific surface area of mechanically activated components allows them to more efficiently participate in cross-linked reactions. The particles of pigment are also crushed and more evenly distributed over the volume of the mixture. Unreacted cement grains after activation process partially lose their concrete coating and can hydrate as well. Used iron oxide pigments washed out of the dense concrete matrix less intensively. Dense surface of concrete shows little colour loss after salt fog exposure in salt-spray chamber. Freeze-thaw tests showed high freeze-thaw resistance of decorative concrete, both at surface and body of concrete elements. However, surface scaling of high-performance decorative concrete appears before reaching the freeze-thaw resistance characteristic (which correlate with previous studies [17, 18]).

The polymer resins introduced in the composition at formation of material interact with concrete mix and form a dense contact zone between the layers of the solidified compound and concrete. The contact zone between layers of hardened concrete mix and polymer resin demonstrates sufficient strength characteristics. Due to casting method, polymer resin could be introduced into hardening concrete mix to the depth of 5 mm. It also could distribute by pores on the surface of the material and furthermore improve freeze-thaw and chemical resistance.

First series of experiments shown that hardened components of light transmitting concrete has sufficient resistance to the mixing between layers, but the strength test shows that the strength of the concrete is much higher than strength of polymer resin (the destruction goes both on the resin and contact zone). Also, transparency and decorative properties were slightly decreased due to introduction of layers between each other.

Next series of samples was formed using the technology of separated cast of materials. First, the main layers of concrete with sufficient workability were made in the form with separating element between them. After the cast of concrete mix, form element was removed and polymer resin was introduced in empty space. Next, samples in forms were hardened in optimal conditions for one day, then the form was removed and the hardening of concrete continued. The samples were tested to find out their strength at age of 7 and 28 days.

Developed material has a compressive strength of about 30 Mpa, strong adhesion of layers (destruction of material due tests goes through the matrix of concrete) and sufficient light transmitting ability.

4. Conclusions

The usage of polymer resins and concrete mixes based on crushed concrete fines, as well as silica fume and polycarboxylate superplasticizers could allow to make effective light transmitting decorative concrete. The main problem of this material is the mixing of the layers, which leads to decrease of decorative and light transmitting properties. In further work it seems appropriate to conduct a more detailed study of the influence of various concrete plasticizers, aggregates (or absence of them [19]), pigments and polymer resins on rheological properties of light transmitting concrete mix to develop an easy and effective technology of layer-by-layer formation of the material.

References
[1] Pagliolico S L, Valerio R M Lo Verso,* Annalisa Torta, Maurizio Giraude, Fulvio Canonico, Laura Ligi, A preliminary study on light transmittance properties of translucent concrete panels with coarse waste glass inclusions, Energy Procedia 78 (2015) pp. 1811 – 1816
[2] Yue Li, Jiaqi Li, Yuhong Wan, Zhiyuan Xu Experimental study of light transmitting cement-based material (LTCM) Construction and Building Materials Volume 96, 2015, pp. 319-325
[3] Evangelista L, J de Brito, “Mechanical behaviour of concrete made with fine recycled concrete aggregates” Cement and Concrete Composites, Vol. 29, 2007, pp 397–401.
[4] Bazhenov Y M, Alimov L A, Voronin V V “Structure and properties of concrete with nanomodifiers based on technogenic waste” EBS ASV, MGSU, Moscow, 2013
[5] Oksri-Nelfia L, Mahieux P-Y, Amiri O, Turcry Ph, Lux J “Reuse of recycled crushed concrete fines as mineral addition in cementitious materials” Materials and Structures, 2016, Vol. 49, pp. 3239–3251.
[6] Eckert M, Oliveira M “Mitigation of the negative effects of recycled aggregate water absorption in concrete technology” Construction and Building Materials, Vol. 133, 2017, pp 416–424.
[7] Pereira P, Evangelista L, J de Brito, “The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates”, Construction and Building Materials, Vol. 28, Issue 1, 2012, pp 722–729.
[8] Buryanov A F, Krivenko V V, Zhukov A D “Marble and methods of its simulation”, EBS ASV, MGSU, Moscow, 2014.
[9] Justnes H, Dahl P A, Ronin V, Jonasson J-E, Elfgren L “Microstructure and performance of energetically modified cement (EMC) with high filler content”, Cement and Concrete Composites, Vol. 29, Issue 7, 2007, pp. 533-541.
[10] Dvorkin L I “Calculated prediction of the properties and design of concrete compositions”, INFRA-Engineering, Moscow, 2016.
[11] Gorbunov G I, Zhukov A D “Scientific bases of formation of structure and properties of building materials”, EBS ASV, MGSU, Moscow, 2016.
[12] Makridin N I, Korolev E V, Maksimova I N “Pattern formation and the structural strength of cement composites”, EBS ASV, MGSU, Moscow, 2013.
[13] Zotkin A G “Concrete with effective admixtures” INFRA-Engineering, Moscow, 2014.
[14] Dvorkin L I, Dvorkin O L “Special concrete” INFRA-Engineering, Moscow, 2013.
[15] Lyapidevskaya O B, Bezuglova E A “Concretes. Technical requirements. Methods of testing”, EBS ASV, MGSU, Moscow, 2013.
[16] Evangelista L, J. de Brito, “Durability performance of concrete made with fine recycled concrete aggregates” Cement and Concrete Composites, Vol. 32, 2010, pp. 9–14.
[17] Alexandre Bogas J, J de Brito, Ramos D “Freeze–thaw resistance of concrete produced with fine recycled concrete aggregates”, Journal of Cleaner Production, Vol. 115, 2016, pp 294–306.
[18] Pilipenko A S, Bazhenova S I Usage of Crushed Concrete Fines in Decorative Concrete. IOP Conference Series: Materials Science and Engineering, 2017, Volume 245.
[19] Carsana M, Tittarelli F, Bertolini L Use of no-fines concrete as a building material: strength, durability properties and corrosion protection of embedded steel. Cement And Concrete Research, 2013. vol. 48, pp. 64-73.