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# UNCONVENTIONAL AND ENVIRONMENTALLY FRIENDLY TECHNIQUE FOR INCREASING THE STRENGTH OF BUILDING MATERIALS THROUGH $CO_2$-ABSORBING AND TRAPPING INSIDE

BY

**LUCIAN PĂUNESCU[1,*], ENIKÖ VOLCEANOV[2,3], ADRIAN IOANA[4] and BOGDAN VALENTIN PĂUNESCU[5]**

[1]Daily Sourcing & Research SRL Bucharest, Romania
[2]Metallurgical Research Institute SA Bucharest, Romania
[3]National University of Science and Technology POLITEHNICA Bucharest, Faculty of Engineering in Foreign Language, Bucharest, Romania
[4]National University of Science and Technology POLITEHNICA Bucharest, Faculty of Material Science and Engineering, Bucharest, Romania
[5]Consitrans SA Bucharest, Romania

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**Abstract.** Self-compacting concrete using the iron dust waste ability to produce $FeCO_3$ by $CO_2$- absorbing/trapping and favouring the increase of concrete strength was designed and tested. Except for iron dust, other materials rich in silica and alumina (clay brick waste and metakaolin) or CaO-rich (calcium carbonate) and a catalyst (oxalic acid) were added to the mixture, forming a carbon-negative binding material. The paper originality was obtained by adopting new methods of intensive hardening the fresh concrete by its immersing or exposure to $CO_2$-enriched mediums, followed by free storage in air for 7 or 28 days for $CO_2$-absorbing (recommended by the inventor). The results showed that replacing the cement with 12.3% carbon-negative material, using usual ratios of sand, coarse aggregate, lignosulfonate, and water and also applying the concrete hardening variant through the two methods of immersing/exposure in $CO_2$-enriched mediums, concrete specimens with highest strength were made.

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*Corresponding author; *e-mail*: lucianpaunescu16@gmail.com

**Keywords:** carbon-negative, self-compacting concrete, iron dust, $CO_2$-absorbing, iron carbonate.

## 1. Introduction

In the last decades, the "green concrete" concept is based on the need to drastically reduce or replace Portland cement in the composition of traditional concrete, the manufacture of which involving high emissions of greenhouse gases into the atmosphere.

Different types of ash in the form of coal fly ash were used in the concrete composition as cementitious materials having the capacity to reduce the impact of concrete manufacturing on the environment. Also, finely ground limestone was used as a partial substitute for cement (in ratios of up to 5%), having the ability to increase the reactivity of cement. The replacement of about 20% cement in the concrete composition with limestone calcined clay pozzolan showed a significant improvement in the concrete strength by comparison with ordinary Portland cement concrete. It was found that the use of the mixture of metakaolin and limestone (in a 2:1 ratio) as cement substitutes up to 60% improves the mechanical strength of concrete (Shinde *et al.*, 2023). A remarkable invention of the American researcher David Stone (Stone, 2002) offered the solution of a new type of construction material called "Ferrock", using the combination of iron dust, coal fly ash, lime powder, metakaolin, and oxalic acid as a catalyst for the reaction with $CO_2$ and water, leading to the formation of iron carbonate. The new Ferrock binding material absorbs $CO_2$ and this process contributes to its hardening. The material is environmentally friendly and at the same time, has a much higher mechanical strength compared to the conventional concrete (Shinde *et al.*, 2023). Ferrock is cheaper, more flexible and stronger compared to traditional concrete and in addition, it represents a carbon-negative alternative to cement. During drying, it absorbs $CO_2$ from the atmosphere forming iron carbonate ($FeCO_3$), which binds this gas into the Ferrock mass (Ferrock, 2018).

Like cement, the Ferrock binding material uses clay and limestone in the manufacturing process, but in much smaller ratios. Most of materials are residual products, of which the majority is iron powder (Lanuza Garcia *et al.*, 2017). According to (Kaenzig de Danus, 2021), Ferrock material is five times stronger than traditional concrete. The strength of this material is predominantly due to the presence of iron carbonate resulted from the chemical reaction between iron dust waste and $CO_2$. Mechanical strength of Ferrock material is within the limits of 34.5-48.3 MPa, some measurements indicating even 69 MPa. By comparison, the traditional concrete needs 1-2 days to harden and up to 28 days to reach the highest mechanical strength, while Ferrock only needs about 7 days to fully harden. During the curing process, it will absorb $CO_2$ from the atmosphere, making the material even stronger. Its resistance to flexure requests allows it to remain crack-free under conditions of more intense stress. In addition, the

Ferrock material is relatively inactive in terms of chemistry. Gases or different chemical products can't cause damage to its configuration. Also, it is resistant to salt water, being considered suitable for marine constructions (Kaenzig de Danus, 2021).

Self-compacting concrete using Ferrock material was designed for the first time in 1988 to allow the creation of durable concrete structures. Further investigations to optimize the techniques for preparing mixtures required for self-compaction were carried out in Japan, Canada, Sweden, The Netherlands, Thailand, and Taiwan (Okamura *et al.*, 2000). Self-compacting concrete has the ability of adequate flowability and optimal compaction under its own weight. the advantages of the new concrete type recommend its use in the construction of bridges, dams, high-rise buildings and infrastructures (Jeffy Pravitha *et al.*, 2023).

The type of Ferrock-based concrete recently patented in the United States acts so that $CO_2$ is absorbed from the atmosphere and contributes to obtaining a stronger, more flexible, and cheaper material compared to traditional cement-based concrete. Several tests have been carried out in the world indicating promising results as well as the fact that this material can be a viable alternative to classic concrete.

Patel and Solanki (2018) carried out experiments on manufacturing concretes of this type replacing between 20-30 wt. % Portland cement with Ferrock material obtained by the reaction between iron dust waste, $CO_2$, and water. Thus, using Ferrock material between 12.7-19.05 $kg \cdot m^{-3}$, by reducing the amount of cement from 63.5 to 44.45 $kg \cdot m^{-3}$, sand (142.84 $kg \cdot m^{-3}$) as fine aggregate, coarse aggregates with dimensions below 20 mm (229.6 $kg \cdot m^{-3}$), superplasticizer additive (0.5 $kg \cdot m^{-3}$), and water (30 $kg \cdot m^{-3}$), the new type of ecological concrete based on trapping $CO_2$ into its mass was manufactured. The slump test of the fresh concrete showed that by substituting up to 30% cement with Ferrock material, a maximum slump of 95 mm was obtained, representing 18.7% more than the normal slump of the reference concrete. The mechanical properties (compression, flexural, and split tensile strength) of the new concrete type were determined after curing processes of 7 and 28 days, respectively. Results showed growing the compression strength after 7 days from 17.89 MPa (at the reference concrete) up to 20.58 MPa and respectively, after 28 days from 27.11 MPa (reference concrete) up to 34.06 MPa. The flexural strength increased from the reference value of 3.40 MPa after 7 days to 3,83 MPa and respectively, from 6.65 MPa after 28 days to 8.32 MPa. Split tensile strength registered increasing from the reference value of 1.90 MPa (after 7 days) to 2.10 MPa and respectively, from 7.82 MPa (after 28 days) to 9.19 MPa.

According to (Jeffy Pravitha *et al.*, 2023), a self-compacting concrete was experimentally produced by replacing Portland cement in proportions between 5-25% with the new type of ecological material-Ferrock, aggregates and superplasticizers. The concrete hardening was carried out by immersion under water, exposure to $CO_2$ as well as a combination of the two methods. Hardening with $CO_2$ allowed reaching 40% of the final strength of the concrete after 4 hours, while the combined use of the two methods led to obtaining the best performances. The optimal degree of cement replacement was 10%, the use of Ferrock almost doubling the strength of concrete. The combined hardening method led to the increase in strength after 28 days by 32.6%. The authors of this paper showed that Ferrock is a combination of a significant proportion of iron waste from the steel industry, iron dust, coal fly ash, metakaolin, and limestone powder. Ferrock is not a cementitious material, it hardens through the carbonation of pozzolanic materials in the presence of oxalic acid, as a catalyst. The results of the research included in the work (Jeffy Pravitha *et al.*, 2023) showed that the material mixtures included for the manufacture of self-compacting concrete containing up to 15% Ferrock led to obtaining satisfactory properties regarding viscosity and flowability, while limiting the proportion of Ferrock to 10% offered excellent concrete hardening characteristics between 7-56 days.

A work published in 2018 (Karuppasamy *et al.*, 2018) refers to a preparing method of Ferrock material including 60% iron powder (with average particle size of 19 µm), 20% class F-fly ash or ground glass particles), 10% limestone powder (average particle size of 0.7 µm, 8% metakaolin, and 2% oxalic acid (as a catalyst). The water/solids ratio was used within the limits of 0.18-0.30. The cured specimens were identified to contain between 8-11 wt. % trapped $CO_2$ (Das *et al.*, 2015).

A relatively similar manufacturing recipe was mentioned in the work (Mohan, 2021), using a mixture containing iron powder (58-67%), fly ash (15-20%), limestone (8-10%), and metakaolin (6 -10%).

The paper (Das *et al.*, 2014) analyzed microstructural features of the new binding material obtained by carbonation of iron powder waste. The binder has in his composition mainly iron powder as well as silica and alumina with an important role in developing the carbonation reaction and forming iron carbonate. High values of compression strength were reached by most concretes produced with this binder. In microstructural terms, it was observed the reduction of material porosity and pore sizes with increasing the carbonation time from 1 day to 4 days.

David Stone's patent (Stone, 2002) includes numerous variants of precursor compositions for obtaining the iron carbonate binder. Iron powder, silica, calcium carbonate, clay (all in powder form), and a fibrous additive are mentioned. Another option includes alumina, kaolinite or metakaolin. In another embodiment, an organic reducing agent and oxalic acid are proposed. Other variants proposed by the inventor included limestone or a derivative of limestone and fly ash. An important version includes iron powder (about 60%), silica (about 20%), calcium carbonate, clay, and a fibrous or woven additive. Also, a recipe where fly ash is the main additive, being added limestone, metakaolin, and an organic acid. Obviously, these achieving variants have a theoretical character, not being practically verified.

Taking into account the experimental results recently obtained in the world, the authors' team opted for adopting an original recipe for preparing the binding material similar to Ferrock. The basic component of the mixture remained the iron powder waste, captured after the purification of waste gases resulted from the industrial process of steel manufacturing, i.e. a by-product of the metallurgical industry. As a silica-rich material, finely ground post-consumer drinking bottle was chosen and as materials with high silica and alumina content, clay brick residues recovered from building demolition together with metakaolin were adopted. Calcium carbonate powder ($CaCO_3$) commercially available at low grain size was also used as a supplier of CaO. Oxalic acid was chosen as a catalyst for the iron carbonate formation reaction.

## 2. Materials and Methods

For preparing the Ferrock type binding material, the following ingredients were used: iron powder waste, ground post-consumer drinking bottle, clay brick waste, metakaolin, and oxalic acid. The iron dust resulted from the purification of waste gases captured from EAF furnaces from Mechel SA Targoviste (Romania), taken in 2010, was examined at the Metallurgical Research Institute SA Bucharest. The dust size was within the limits of 3-85 µm, of which about 85% was represented by particles below 5.5 µm. The chemical composition of the dust was analyzed with the AXIOS-sequential X-ray fluorescence spectrometer, indicating the following weight proportions of its components: 54.6% $Fe_2O_3$, 7.2% MnO, 6.3% CaO, 6.0% $SiO_2$, 4.1% MgO, 1.5% ($Na_2O$ + $K_2O$), 0.9% $Al_2O_3$. The batch of iron dust was partially stored and used in this experiment, given that the production activity of the mentioned company was stopped three years later.

Clay brick waste recovered from the building demolition and ground in the form of a fine powder below 40 µm was used due to its high content of silica ($SiO_2$) of 54.9% and alumina ($Al_2O_3$) of 23.4%. Relatively small amounts of iron oxide ($Fe_2O_3$) of 4.8%, lime (CaO) of 0.5%, and other compounds in negligible proportions completed the chemical composition of this waste.

Metakaolin is a calcined clay type, coming from the calcination process of kaolinite. It is a high reactive pozzolana (Siddique and Cachim, 2008). In chemical composition terms, metakaolin is significantly richer in silica and alumina compared to the clay brick waste, but obviously more expensive. According to (Thankam and Renganathan, 2020), the composition of metakaolin includes 50-60% $SiO_2$, 30-40% $Al_2O_3$, below 2% MgO, 0.5-5% $Fe_2O_3$, 0.5-1.5% $K_2O$, below 0.5% CaO. The particle size of commercially available white metakaolin (originating from China) used in this experiment was chosen under 40 µm.

Calcium carbonate ($CaCO_3$) commercially available at low grain size below 5 µm was used as a supplier of calcium oxide (about 47%).

Oxalic acid $(CO_2H)_2$ was used in the material mixture for favouring the chemical process of iron carbonate formation as well as for homogenizing the mixture. Despite the small amount, the oxalic acid has a special utility because it helps the precipitation and mineralization of iron. The acid role is already known in the metallurgical industry due to its ability to dissolve iron, prevent oxidation, and absorb $CO_2$ with the formation of iron oxalate (Lanuza Garcia *et al.*, 2017).

In terms of dosing the material components for the manufacture of carbon-negative material with features approximately similar to Ferrock, the authors' team adopted a unique manufacturing recipe for all the tested variants, the differentiation being done by the chosen hardening method. Thus, the mixture composition included the material dosages shown in Table 1.

**Table 1**
*Mixture composition for preparing the carbon-negative material*

| Composition | Iron powder | Glass powder | Clay brick waste | Metakaolin | Calcium carbonate | Oxalic acid |
|---|---|---|---|---|---|---|
| Weight ratio (wt. %) | 61.0 | 19.5 | 9.0 | 4.0 | 6.0 | 0.5 |

As can be seen, the manufacturing recipe is quite different from the recipes applied in previous experiments mentioned above, firstly, by using clay brick waste recovered from building demolition as the main supplier of $SiO_2$ as well as reducing (in half) the usual proportion of metakaolin.

After preparing the innovative paste binding material, as a partial substitute for Portland cement, the experimental concrete manufacturing required the use of some traditional materials: ordinary Portland cement type I, fine aggregate (quartz sand) with particle size below 3 mm, selected by sieving, coarse aggregate from gravel with dimensions below 20 mm, sodium lignosulfonate (below 15 µm) as an additive used for reducing the water requirement, improving the fluidity and workability of concrete, and increasing the compression strength as well as water.

According to the theory developed by the inventor David Stone, the carbonation reaction for the formation of iron carbonate, which determines the strong hardening of the new material, takes place in two stages (Valle, 2020). In the first, through the contact of iron dust with water and carbon dioxide absorbed from the atmosphere during the mixture drying, dissociation occurs into $Fe^{2+}$ cation and bicarbonate anions ($HCO_3^-$), while gaseous hydrogen is released. In the second stage, iron cation associates with bicarbonate anions resulting in stable iron carbonate ($FeCO_3$), gaseous $CO_2$, and liquid water. Combining the two stages results in the following form of the carbonation chemical reaction:

$$Fe\ (solid) + CO_2\ (gas) + H_2O\ (liquid) = FeCO_3\ (solid) + H_2\ (gas) \quad (1)$$

The manufacturing method of self-compacting concrete using the carbon-negative binding material (in form of a paste) as a partial substitute for Portland cement was adopted by the authors by mixing these materials together with the other ingredients mentioned in chapter 2.1. The dosage of the mixture components was chosen in particular taking into account the different manufacturing recipes previously tested by researchers. A single recipe was adopted, including Portland cement (12.1%), carbon-negative binding material (1.7%) representing a cement replacement rate of 12.3%, quartz sand (33%), coarse aggregate (53%), sodium lignosulfonate (0.2%), and supplementary water. Knowing the approximate values of materials density (3.15 $g \cdot cm^{-3}$ for cement, 5.29 $g \cdot cm^{-3}$ for carbon-negative binding material, 1.43 $g \cdot cm^{-3}$ for sand, 2.74 $g \cdot cm^{-3}$ for gravel as coarse aggregate, and 1.2 $g \cdot cm^{-3}$ for lignosulfonate as an additive), the quantities corresponding to dry mixture components were calculated (Table 2).

**Table 2**
*Dry mixture composition for preparing self-compacting concrete*

| Composition | Portland cement type I | Carbon-negative binding material | Quartz sand | Coarse aggregate | Sodium ligno-sulfonate | Added water |
|---|---|---|---|---|---|---|
| Amount ($kg \cdot m^{-3}$) | 381.2 | 89.9 | 471.9 | 1452.2 | 2.4 | 551.4 |

According to the literature (Lanuza Garcia *et al.*, 2017), water used in this experimental process (recommended water/solids ratio is within the limits of 0.18-0.30) is considered as a mass-transfer facilitating agent and it does not participate in chemical process.

Three original techniques for hardening by carbonation of this special concrete type were designed and applied after the fresh material was poured into two types of molds (cubic and rectangular) in order to test the values of compression strength and respectively, flexural strength of concrete specimens. After removing from the molds, different hardening processes in three versions of the specimens followed.

Variant A consisted of immersing the specimen in water taken from the municipal supply network, followed by standing in atmospheric air for hardening through the free absorption of $CO_2$. The total duration of this process was 24 hours. Then, the specimen was stored outdoors (under a roof) for 7 and 28 days, respectively.

Variant B consisted of immersing the specimen in $CO_2$-enriched water, followed by placing it in a sealed enclosure whose atmosphere was enriched with $CO_2$ blown in from a pressure gas tank. The total duration of the process was 48 hours. Then, the sample was stored outdoors for 7/28 days.

Variant C was characterized by immersing the specimen in $CO_2$-enriched water for 72 hours. Then, the specimen was maintained outdoors for 7/28 days.

Known methods for investigating the characteristics of self-compacting concrete were applied.

Bulk density was measured using Archimedes' method by the water intrusion technique (ASTM D792-20). The determination of the compression strength was performed with 100 kN-compression fixture Wyoming Test Fixture (A practical guide, 2018). The flexural strength was identified by carrying out the three-point bend test on the specimen (SR EN ISO 14125: 2000). Measuring the water-absorbing capacity of specimens was performed by the immersing method of the material under water (Dyg Siti Quraisyah *et al.*, 2021) according to ASTM D570. Microstructural appearance of samples was examined with Biological Microscope MT5000 model (1000 x magnification). The slump test of fresh concrete was performed with T500 test and V Funnel Test Apparatus was used to determine the flow time of freshly mixed self-compacting concrete.

## 3. Results and Discussion

According to (Lanuza Garcia *et al.*, 2017), the fresh paste containing the carbon-negative binding material, obtained before the aggregate addition for manufacturing the self-compacting concrete, proved to be stronger than the Portland cement paste and the duration required for hardening is greatly decreased to only four carbonation days, compared to 28 hydration days that are necessary for cement to harden. Preliminary tests have shown that the slumping test of an ordinary fresh concrete sample based on integral cement is at least 15% lower than the similar test of the self-compacting concrete sample containing the carbon-negative binding material substituting 12.3% Portland cement (i.e. the cement replacement rate adopted in this experiment).

As mentioned above, two specimen types in dimensional terms were manufactured: cubic with a side of 130 mm and respectively, rectangular with dimensions of 100 x 100 x 240 mm to facilitate the measurement of mechanical strength (compression and flexural). The appearance of these specimens is shown in Fig. 1.

1a 1b 1c

2a 2b 2c

Fig. 1 – Appearance of self-compacting concrete specimens in the form of cubes and bars prepared for determining compression and flexural strengths
1a, 2a – version A; 1b, 2b – version B; 1c, 2c – version C.

The main physical and mechanical features of self-compacting concrete specimens experimentally produced (bulk density, water-absorbing, compression strength, and flexural strength) are presented in Table 3.

**Table 3**

*Main physical and mechanical features of self-compacting concrete specimens*

| Variant | Bulk density after 28 days ($kg \cdot m^{-3}$) | Water-absorbing after 28 days (vol. %) | Compression strength (MPa) | | Flexural strength (MPa) | |
|---|---|---|---|---|---|---|
| | | | After 7 days | After 28 days | After 7 days | After 28 days |
| A | 2398 | 3.3 | 21.6 | 32.8 | 3.3 | 7.5 |
| B | 2408 | 3.5 | 23.5 | 36.5 | 3.8 | 8.3 |
| C | 2413 | 3.6 | 24.9 | 38.4 | 4.0 | 8.9 |

The only bibliographic source that mentions applying the technique of immersion under water of fresh concrete for the purpose of hardening as well as the combined technique of immersion and exposure to absorbing the gaseous $CO_2$ from the atmosphere was the work (Jeffy Pravitha *et al.*, 2023). Practically, the current paper proposes three technical variants of hardening the mixture predominantly containing iron dust, used for producing self-compacting concrete, in all of these, immersion under water being applied, but in different ways. Thus, variant A used ordinary water from the municipal supply network, while variants B and C used, as an original solution, water enriched in $CO_2$ by blowing gas under pressure to simultaneously provide the necessary water and $CO_2$ for iron carbonation. The method of variant A continued with the exposure of the specimen removed from water for the free absorption of atmospheric $CO_2$, the total duration of the carbonation process being 24 hours. Periods of 7 and 28 days of storage in atmospheric air completed the process. In variant B, the specimen removed from the water vessel was subjected to a forced carbonation process with $CO_2$ in an atmosphere enriched in $CO_2$. The total duration of the combined carbonation process was double (48 hours). It was followed by the usual free air storage of the specimen for 7/28 days. Variant C applied the method of immersing the sample under $CO_2$-enriched water, the carbonation duration being 72 hours. This process was followed by free curing in air for 7 and 28 days.

In terms of values, variant C is considered the best of the three tested variants, reaching the highest compression strength values measured after 7 days of air storage (24.9 MPa) and after 28 days (38.4 MPa). Also, the flexural strength reached high values both after 7 days (4.0 MPa) and after 28 days (8.9 MPa). Therefore, it was experimentally proven that the iron carbonation process by immersing the specimen in $CO_2$-enriched water for 72 hours constitutes an effective mixed procedure for the primary forced formation of $FeCO_3$ in a relatively short period of time, which can then be continued by storing the material in free air and the $CO_2$ absorption from the atmospheric air to be made as provided by the inventor David Stone.

By comparison with values of compression and flexural strengths reported in the work (Jeffy Pravitha *et al.*, 2923), the performances achieved in the current paper were higher both after 7 days (between 19.55-21.56 MPa) and after 28 days (between 26.68-34.06 MPa) in in the case of compression strength and respectively, in the case of flexural strength (between 3.27-3.83 MPa after 7 days and between 7.13-8.32 MPa after 28 days).

The microstructural analysis of the specimens presented in Fig. 2 showed that by increasing the carbonation time from 24 to 72 hours, corresponding to variants A-C, the porosity and pore size reduction of the carbon-negative materials took place, corresponding also to the observations of (Das *et al.*, 2014).


a b c **|---------| 80 µm**

Fig. 2 – Microstructural images of self-compacting concrete specimens
a – version A; b – version B; c – version C.

The more compact microstructure with smaller pore sizes favourably influences the mechanical strength of self-compacting concrete specimens.

Self-compacting concrete type based on the ability of iron dust to react with water and $CO_2$ forming $FeCO_3$ was made in experimental conditions for the first time in Romania. Starting from the basic design data of the inventor David Stone, the authors' team of the current paper developed new methods of accelerating the carbonation process by increasing the contribution of $CO_2$ in this process. The $CO_2$-enrichment of water and air in which specimens were kept, contributed to supplementary increasing the strength of material compared to the time of their storage in atmospheric air for $CO_2$-absorbing. However, this contribution could not be satisfactorily quantified at this stage of the research.

Other important aspect constituted by the new value of concrete durability, also mentioned by authors of other works in this field, could not be determined yet because the tested technique is too recent.

## 4. Conclusions

The work aimed to experimentally find new ways to improve the recent innovative technique of preparing carbon-negative binding material as a partial substitute of the usual ordinary Portland cement and implicitly, for the manufacture of self-compacting concrete, using iron dust waste for producing $FeCO_3$ through $CO_2$-absorbing and trapping inside its mass. The method patented by David Stone is based on the ability of iron dust in the presence of water and some silica and alumina-rich materials to absorb $CO_2$ from the atmospheric air during the material hardening. The current paper tested original methods of intensive hardening of fresh concrete by immersing and exposing the material in $CO_2$-enriched environments (water and air, respectively), followed by applying the method developed by the inventor to expose the concrete samples to air during the hardening (7 or 28 days) in order to absorb $CO_2$ from the atmosphere. The results were promising, the compression and flexural strength values reaching higher levels than those obtained only by $CO_2$-absorbing from atmospheric air. The time of testing the behaviour of the new building materials after completing the mentioned treatment was obviously too short to obtain clear conclusions, a fact also observed by other researchers, so that an additional supervision of specimen properties for at least 6 months or more is necessary.

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## TEHNICĂ NECONVENȚIONALĂ ȘI ECOLOGICĂ PENTRU CREȘTEREA REZISTENȚEI MATERIALELOR DE CONSTRUCȚIE PRIN ABSORBȚIA ȘI CAPTURAREA $CO_2$

(Rezumat)

A fost conceput și testat un beton autocompactant utilizând capacitatea deșeului din praf de fier de a produce $FeCO_3$ prin absorbția/capturarea $CO_2$ și favorizarea creșterii rezistenței betonului. Exceptând praful de fier, alte materiale bogate în silice și alumină (cărămidă de argilă reziduală și metacaolin) sau bogate în CaO (carbonat de calciu) și un

catalizator (acid oxalic) au fost adăugate în amestec, formând un material liant cu carbon negativ. Originalitatea lucrării a fost obținută prin adoptarea unor noi metode de întărire intensivă a betonului proaspăt prin imersia sau expunerea lui în medii îmbogățite în $CO_2$, urmate de stocarea liberă în aer pentru 7 sau 28 zile pentru absorbția $CO_2$ (recomandată de inventator). Rezultatele au arătat că înlocuirea cimentului cu 12,3% material cu carbon negativ, utilizând proporții uzuale de nisip, agregat grosier, lignosulfonat și apă și de asemenea, aplicând varianta de întărire a betonului prin cele două metode de imersie/expunere în medii îmbogățite în $CO_2$, au fost fabricate probe de beton cu cea mai mare rezistență.