

építőanyag

A Szilikátipari Tudományos Egyesület lapja

Journal of Silicate Based and Composite Materials

A TARTALOMBÓL:

- Hinged doors opening-force in pressurized stairwells
- Fracture as a sample preparation method for SEM analysis: implications for basalt
- Advancing sustainability in construction: a review of supplementary cementitious materials and their environmental impact
- Punching shear strengthening of the flat slab using SIFCON

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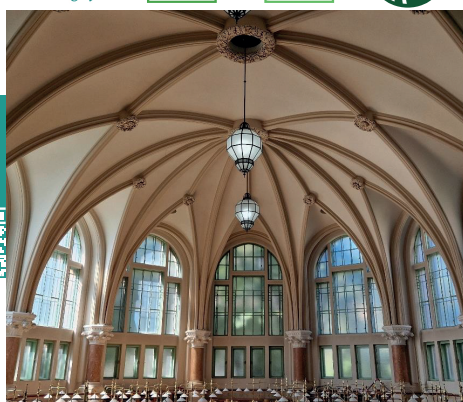
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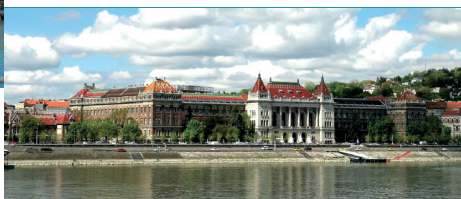
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Hinged doors opening-force in pressurized stairwells

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Abstract

The ability to evacuate buildings is one of the most important pillars of safety. Internal stairwells providing vertical access must be designed to protect against smoke spread while ensuring escape routes. One commonly used method of smoke extraction is to create positive pressure in the stairwell, also known as pressurization. In many cases, doors leading to such stairwells are equipped with escape-supporting locking devices, the primary purpose of which is to ensure easy opening. These panic bar doors ensure that the locking mechanism can be released even in an emergency. However, when using pressurization, the torque generated by the pressure difference between the two sides of the door must also be overcome in order to open the hinged door.

The study investigates the opening force of doors in pressurized stairwells, considering different opening solutions and pressure values. In addition to mechanical tests, it also evaluates the role of building materials, with particular regard to the rigidity of the door leaf, the behavior of seals, and the material and design of the connection between the frame and the wall.

The results show that optimizing door opening force is not only a structural issue, but also a matter of material selection. The author proposes a labeling system that supports the proper design of doors used in pressurized environments based on the materials and structural details used.

Keywords: pressurization, door opening force, escape routes, panic bar, pressurized stairwell
Kulcsszavak: túlnyomásos, ajtónyitási erő, menekülési útvonalak, pánikvasalat, túlnyomásos lépcsőház

1. Introduction

Combustible substances often have dangerous chemical properties [1] which, in the event of an emergency situation, together with toxic combustion products spreading in the event of a major building of industrial fire, can further endanger the human health and the environment [2].

Pressurized smoke-free stairwells reduce the entry of smoke and toxic combustion gases into smoke-free spaces when doors are closed by means of overpressure created by the introduced air, without obstructing access to the stairwell. In this case, flows are mainly through small cross-sectional gaps and cracks [3]. One of the most important aspects of pressurized ventilation systems is how they can affect door opening forces [4]. If the relative overpressure in the stairwell is too high, the force required to open doors leading to the stairwell increases, which can be an obstacle for people escaping to the stairwell [5]. In mechanical systems, care must be taken to ensure that door opening forces are complied with [6]. This can be achieved by regulating the speed of the fans and by using devices to dissipate excess pressure. Frequency converters are often used to regulate the amount of air supplied by the fan(s), which are primarily controlled by pressure transmitters.

It is generally accepted that traditional masonry structures can withstand pressures of 500 Pa, while lightweight structures, such as assembled plasterboard partitions, can only withstand pressures of 250 Pa. Certain types of structures may have even lower limits [7]. The material and structural characteristics of door systems – including door leaf rigidity, the behavior of the sealing materials under pressure, the airtightness performance of the sealing profiles, and the structural interaction between the door frame and the surrounding wall – all play a critical role in determining the amount of force required to open the door.

The harmonized European standard for the design of pressure differential systems is EN 12101-13. According to this standard, systems must be designed so that the force required to open the door does not exceed 100 N at all levels and on all doors in escape routes [8]. According to NFPA 92, which focuses on the design of smoke control systems, the maximum force required to open a door must not exceed the value specified in NFPA 101 or in state or local codes and regulations [9]. According to NFPA 101, the pressure difference between door openings must not exceed the value at which door leaves can be opened with a force greater than 133 N. According to the IBC, if a door must be fire rated, the force required to be set in motion the door shall not exceed 133 N [10].

According to standard AS/NZS 1668.1:1998, regardless of whether the exits are under pressure or not, the maximum force required to open doors must not exceed 110 N, thus ensuring that the exits can be used in all cases [11].

According to TRVB 112 S, the pressure difference caused by the overpressure ventilation system must not affect the opening of doors and the reliable closing of door closers, therefore appropriate measures must be taken to ensure that the force required to open the door does not exceed 100 N [12]. According to VDMA 24188, the maximum pressure difference must be limited so that the door opening force measured at the door handle does not exceed 100 N, so that the doors remain openable for weaker persons and so that they do not give the impression to people escaping that the door is locked [13].

In Hungary, most fire protection designers and experts prefer the solutions proposed in the fire protection technical guidelines [14]. Fire protection technical standards can be applied in various ways in relation to fire protection design, installation and use [15-17]. According to fire protection

technical guidelines in field of protection against heat and smoke spread, the openability of doors in pressurized stairwells or vestibules is ensured if the force required to open them does not exceed 100 N in normal cases. In special cases (e.g., accessibility), this value may be lower [18].

The EN 179 standard tests the force required to operate lever handles and push bars [19]. The force required to operate panic bars is specified in standard EN 1125. When using a panic bar, the force required to open the lock mechanism of an unloaded door must not exceed 80 N [20]. Doors in pressurized smoke-free stairwells are typically equipped with self-closing devices. The requirements for self-closing door closers are specified in standard EN 1154, among others [21].

Overall, it can be concluded that various standards and technical guidelines generally recommend a maximum door opening force of around 100-130 N. In the case of accessibility designs, this value may be significantly lower. The harmonized European standards for emergency exit devices operated by a lever handle or push pad, furthermore horizontal bar, for use on escape routes, examines the force required to operate the lock mechanism when testing the force required to open the door. The harmonized European standard for controlled door closer devices refers to the weight and width of the door mechanism operated by the door closer according to different classes.

2. Material and methods

Two types of force measuring instruments were used during the measurements (Fig. 1). One of them is a calibrated digital push/pull force gauge with peak-hold function. The measuring range of the instrument was 1 kN, with a resolution of 0.5 N and an accuracy of 0.5% of the measuring range. The other instrument is a spring force gauge with a measuring range of 0-156 N with a maximum indicator. At least three opening force measurements were performed at each measurement point. In order to ensure that successive measurements were taken at exactly the same point, a red marker was affixed to the axis of force.

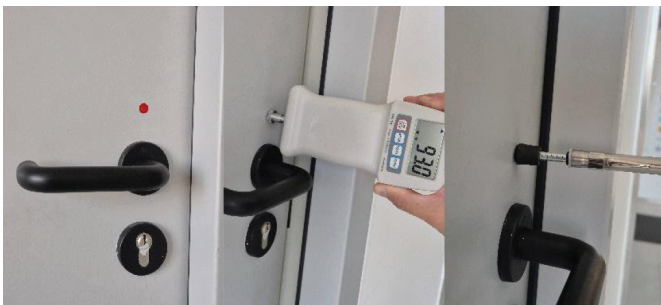


Fig. 1 Measurement of opening force at marked measuring points using a digital and spring force gauge

1. ábra Ajtónyitási erő mérése a megjelölt mérési pontokon digitális és rugós erőmérővel

2.1 Method and tools for measuring opening force

Comparative measurements were performed on a test door to check the reliability of the spring force gauge. In the first test, the fan in the pressurized smoke-free stairwell was switched off. In the second case, the fan was in operation. During the test, the pressure difference between the two sides of the door

was measured with a calibrated differential pressure gauge. The door tested had a fire resistance rating of 90 minutes and was equipped with a self-closing mechanism in accordance with EN 1154. The door was 1080 mm wide and 2142 mm high, with the handle 90 mm from the latch, and a total weight about 145 kg. The distance between the hinge and the edge of the door leaf was 15 mm. The door was installed in a 20 cm thick reinforced concrete wall, and the gaps between the frame and the wall opening were filled with fire-retardant foam. The door was bordered by ceramic cladding at the bottom, and the slabs were made of 28 cm thick reinforced concrete.

When a hinged door opening into a positive pressure area is opened, the total torque acting around the hinge at the moment of opening can be described by the following equation [22].

$$M_r + A \cdot \Delta p \cdot \left(\frac{W}{2}\right) - F \cdot (W - d) = 0 \quad (1)$$

Where

F is the total door-opening force (N)

M_r is the moment of door closer and other friction (Nm)

W is the door width (m)

A is the door area (m²)

Δp is the pressure difference across door (Pa)

d is the offset (the distance that the door-opening force is offset from the latch side of the door) (m)

Based on Equation (1), we can infer that the force required to open the door must cover the opening torque of the door closer, the resultant force on the door leaf by the overpressure, the resultant of which acts at the center of the door leaf, and the torque resulting from other losses (e.g., friction).

2.2 Single-leaf door with lever handle and panic bar.

If the number of occupants of the area, their knowledge of the premises or other factors affecting their evacuation so warrant, emergency exit or panic locks may be required on doors leading to pressurized spaces. If the door opens into a pressurized area, such as a pressurized smoke-free stairwell, it is important to consider where and how much force is required to open the door when operating the handle or panic bar. Fig. 2 illustrates the significant differences between the use of a handle and a bar.

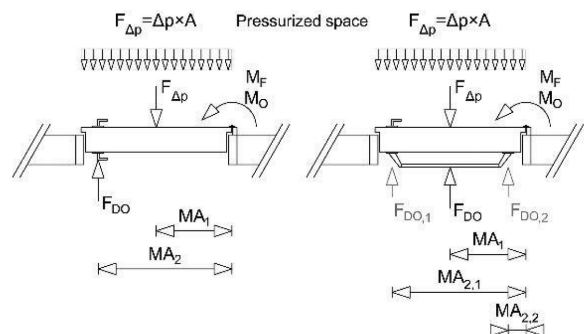


Fig. 2 Door opening into a pressurized space; effect of the opening mechanism on the opening force

2. ábra Túlnyomásos térbe nyíló ajtó; a nyitószerszerek hatása a nyitási erőre

The distributed force resulting from the overpressure of magnitude Δp acts on the surface area A of the door leaf. The resulting force is $F_{\Delta p}$, which exerts a torque against the opening

with a force arm MA_1 . When a handle is used, F_{DO} is the force required to open the door, which acts with force MA_2 against the opening torque M_O , the friction torque M_F and the torque resulting from overpressure.

When using a panic bar, if it is fixed at two points on the door leaf, the force required to open the door acts at two points. In this case, the opening force F_{DO} is balanced by the reaction forces $F_{DO,1}$ and $F_{DO,2}$ (which are shown as action forces in the figure for illustrative purposes). The $F_{DO,1}$ force is associated with the $MA_{2,1}$ force arm, while the $F_{DO,2}$ force is associated with the $MA_{2,2}$ force arm. It follows that in the latter case, the door opening mechanism is more reliable, but due to the method of force transmission, the force required to open the door is more sensitive to the pressure difference between the two sides of the door. The force required to open the door increases as it approaches the hinge.

3. Results and discussion

3.1 Measurements with digital force gauge and spring force gauge

Two series of measurements were performed. In the first series, the overpressure ventilation was not in operation, and there was an approximate pressure difference of 0 Pa between the two sides of the closed door. In the second series, the overpressure ventilation was in operation, resulting in an average overpressure of 56.6 Pa opposite the opening. The results of the measurements are shown in Table 1.

Fan	Measured opening force with digital force gauge (N)			Measured opening force with spring force gauge (N)		
OFF	35,5	36,5	35,5	39	40	40
ON	91,5	90,5	91,0	90	90	90

Table 1 Comparative measurements with spring and digital force gauges, with and without differential pressure.

1. táblázat Összehasonlító mérések rugós és digitális erőmérővel, nyomáskülönbséggel és anélkül

The values measured with the simple spring-loaded device showed good agreement with the measurement results of the calibrated digital gauge. The hand-held device was suitable for measuring the opening force with the fan switched on and off. The door opening force did not exceed 100 N even at an overpressure of more than 50 Pa.

3.2 Opening force measurement on double-leaf panic bar doors

In the next test, a door fitted with a panic bar that met the EN 1125 standard was tested. The panic bar covered 80% of the door width. During the standard test, the force required for operation is tested in the middle and at both ends of the bar. The door tested was 1350 mm wide and 2062 mm high. The panic bar transferred the force to the door leaf at a distance of 80 and 1270 mm from the hinge. The door leaf weighed approximately 180 kg and equipped with EN 1154 door closer device. A mark indicating the opening mechanism was located in the center of the door tested. The force required for opening was therefore measured in the center of the bar and at both edges (Table 2). The smoke extraction system was not in operation during the measurements.

Position	Measured opening force (N)			Mean (N)	Calculated opening torque (Nm)
Left side	34,0	34,0	36,0	34,7	38,12
Middle	57,0	58,0	59,0	58,0	39,15
Right side	208	207	210	208,3	40,46

Table 2 Opening force measured at different points on the panic bar and calculated opening torque

2. táblázat A pánikvasalat különböző pontjain mért nyitási erő és a számított nyitónyomaték

The measurement results clearly show that the force required to open the door is significantly influenced by where the force is applied on the panic bar. Even with a door closer, the force required to open the door remained below 80 N in the middle of the panic bar and at the end closest to the latch when the pressurization system was not in operation.

In the following case, the pressurized smoke-free stairwell supply fan was operating and created a pressure difference of approximately 48 Pa between the two sides of the door leaf. The opening force was then measured again (Table 3), but only in the middle of the bar and at the end near the latch, as opening would have required a disproportionately large force near the hinge.

Position	Measured opening force (N)			Mean (N)	Calculated opening torque (Nm)
Left side	122,5	120,0	121,5	121,3	141,56
Middle	200,5	201,0	204,5	202,0	136,35
Right side	-	-	-	-	-

Table 3 Opening force measured at different points on the panic bar and calculated opening torque during operation of the stairwell pressurization system

3. táblázat A pánikvasalat különböző pontjain mért nyitási erő és számított nyitónyomaték a lépcsőházi túlnyomásos rendszer működése közben

The measurement results clearly show that, while ensuring an overpressure of around 50 Pa in the stairwell, it was not possible to ensure the force required to open the door (maximum 100 N) even in the area closer to the panic bar latch.

In the case of double-leaf doors, if the design is symmetrical, the force exerted on the second leaf is even more unfavorable, regardless of whether the pressurization system is in operation or not. In this case, depending on the design of the rebate, the surface area exposed to overpressure is greater at the moment of opening, and the opening torque of the first leaf must also be overcome (Fig. 3).

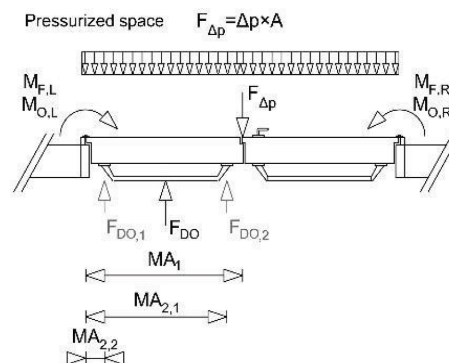


Fig. 3 Force required to open a double-leaf door opening into a pressurized space, measured at the center of the second door leaf.

3. ábra Túlnyomásos térbe nyíló kétszárnyú ajtó nyitásához szükséges erő, a második ajtószárny közepén mérve

Based on calculations and measurements, it can be concluded that in the case of doors equipped with panic bars, the force required to open the door was lowest on the side of the bar latch on the first opening leaf. EN 179 and EN 1125 recommend that the opening mechanism be marked directly above or on the operating mechanism. The door forms part of a smoke-free stairwell with positive pressure, therefore, unlike the general use of panic locks, additional markings may be necessary to ensure safe operation. The author illustrates the recommended method of marking in Fig. 3.

3.3 Discussion

Various international standards typically recommend between 100 N and 133 N as the maximum force required to open doors in general [8-13, 18]. Some standards differ between doors that must be fire rated [10]. In pressurized stairwells, the force required to open the door may ultimately limit the maximum pressure difference between the two sides of the door leaf.

Since stairwells are typically evacuation routes, in some cases, an easily openable locking mechanism is required, for which test standards examine the force required to release the locking mechanism. In these tests, the door leaf is not under positive pressure in the direction of opening [19, 20].

The results of measurements taken with the spring-loaded gauge showed good agreement with the values measured with the calibrated digital gauge.

Tests on doors with handles showed that even with an overpressure of more than 50 Pa, the force required to open the door did not exceed 100 N. This was due to the favorable force distribution and the dimensions of the door leaf.

During the test, the force required to open the single-leaf door fitted with a panic bar was less than 80 N at the center of the bar and at the end of the bar closer to the lock, without any pressure difference, which is in good agreement with EN 1125. The opening torque value complied with class 3 of EN 1154 [21].

When the stairwell pressurization system was in operation and there was an average pressure difference of 48 Pa between the two sides of the door leaf, the force required to open the tested door increased significantly. Approximately 200 N was measured in the middle of the panic bar. At the end of the bar closer to the latch, the force was approximately 120 N, which still complies with certain regulations.

In addition to the design of the locking mechanism, differences in opening force can also be attributed to material and structural factors. These include, for example, the stiffness and deformation behavior of the door leaf (depending on the core material and manufacturing method), the compressibility and aging properties of the sealing rings, and the stiffness of the connection between the frame and the wall. The structural compliance of the deformation caused by overpressure can also influence the uniformity of the seal and load transfer, which in turn affects the force required to overcome static friction and air resistance.

The results of the research showed that if the door opening mechanism is symmetrically positioned on the door leaf and the door opens into a pressurized stairwell, the part of the opening mechanism on which the opening force acts has a significant influence on the force required to open the door. Based on this, recommendations can be made for the designation of opening mechanisms for doors opening into pressurized stairwells in certain cases.

A further research direction could be the interpretation of the scientific problem examined in this article in terms of its application in pressurized rooms installed in chemical industry establishments and chemical warehouses, such as in industrial buildings serving the operation of facilities or emergency management [23].

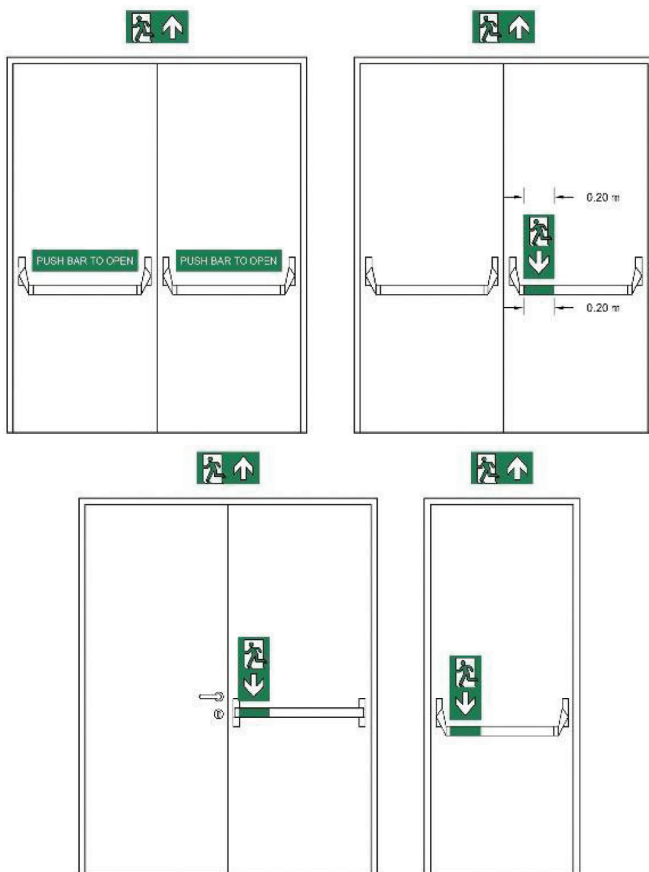


Fig. 4 Mark the opening mechanism of doors opening into pressurized spaces at the point where the opening force is lowest, using pictograms and labeling.

4. ábra Túlnyomásos térbe nyíló ajtók nyitószervezetének megjelölése piktogramokkal és feliratokkal azon a ponton, ahol a nyitási erő a legalacsonyabb

The first door in Fig. 4 shows the standard marking for panic bar doors. Since in this case both the operating mechanism and the markings are symmetrical, it is not possible to determine clearly at which point the minimum opening force must be applied. On the other doors, the part of the operating mechanism where the least force is required to open the door is marked in green. For better visibility, the markings recommended by ISO 7010 have also been added to the doors above this part. It is important to note that the opening mechanism of panic locks is safer than other designs. Doors opening into pressurized smoke-free stairwells are considered special applications, where the use of the markings described above is recommended to increase opening safety.

4. Conclusions

Based on the research carried out in this study, the following final conclusions can be drawn:

1. A digital or spring-loaded force gauge can be used to measure the force required to open the door.
2. By positioning the locking mechanism correctly and limiting the size of the door leaf, the force required to open the door can be limited to below the specified values.
3. In the case of doors equipped with panic bars, depending on the design of the panic bar, the force required to open the door may be greater in the middle of the symmetrically designed bar if the door opens into an pressurized stairwell.
4. In the case of doors equipped with panic bars, the force required to open the door on the side of the bar closest to the latch was found to be lower based on measurements.
5. It is recommended that, in the case of doors opening into stairwells with positive pressure, where justified by the design of the door and the locking mechanism, the section of the panic bar requiring the least force to open be marked.
6. The recommended method of marking is to mark part of the bar with a color and to use a marking composed of the symbols of ISO 7010, which does not conflict with the marking recommended in the annex to EN 1125.
7. Materials and structural factors – such as door leaf stiffness, mechanical behavior of seals, and door frame-wall connection stiffness – can influence opening force, especially under pressurized conditions. These factors, along with hardware design and pressure control, should be considered critical design criteria.

Conflicts of interest

There is no conflict of interest

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Fracture as a sample preparation method for SEM analysis: implications for basalt

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Abstract

Revealing of full assemblage of accessory minerals is essential for genetic modelling of any geological object. Here we discuss a method for preparing basalts for High Resolution Scanning Electron Microscopy (HR-SEM) analysis for this purpose. This method involves fracturing samples under identical conditions using an Izod pendulum. The fractures in a sample primarily propagate along grain boundaries, their interstices, and mineral inclusions, which concentrate stress; therefore, submicron mineral grains are more likely to be exposed on fractured surfaces than on polished surfaces. Here, fresh fracture surfaces were investigated in basalt samples from the Etna vents and the Tolbachik fissure zone. Crystals of minerals containing zinc, copper, nickel, sulfur, and iron were identified on fresh fracture surfaces. The morphology of submicron crystals of apatite, orthopyroxene, spinel, and copper sulfide was revealed. These crystals were not observed on polished thin sections of these specimens as they were either not brought to the surface or were chipped out. The unambiguous morphology of submicron inclusions in orthopyroxene and olivine was shown for the first time. In contrast to the thin-section surface, the fractured surface retains clear evidence of zoning in rock-forming minerals. Additionally, the distribution of accessory minerals, the morphology of crystals in pores, which is fundamentally impossible to see in thin section, and the composition of minerals within inclusions are more reliably represented on the fracture surface. Based on these findings, we suggest fracture surfaces should be more widely studied in petrogenetic research.

Keywords: HR-SEM, basalt, fracture surface, submicron inclusions, accessory minerals, Izod pendulum

Kulcsszavak: HR-SEM, bazalt, törési felület, szubmikronos zárványok, járulékos ásványok, Izod-féle ütőmű

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1. Introduction

Rock samples are commonly prepared for Scanning Electron Microscopy (SEM) analysis as thin or polished sections [1, 2]. Accurate quantitative Energy Dispersive Spectroscopy (EDS) as well as Wave Dispersive Spectroscopy (WDS) analysis can only be performed on thin or polished sections [3]. However, a thin section or polished section represents a random cut of the rock and mineral grains within it. This section only shows some of the mineral grains in the rock or the shapes of the crystals and their aggregates that the cut accidentally passed through. Additionally, accessory minerals may be absent within the polished surface and remain inaccessible for analysis. Besides, the preparation of thin sections is also commonly associated with the formation of artifacts, the most frequent of which are phase chipping, cracks, and surface contamination, caused by grinding and polishing [2, 4]. Epoxy impregnation helps reduce the number of lost phases, new cracks, introduced during sample preparation, but it has its drawbacks [5]. For example, epoxy resin fills pores and other negative relief forms, which, on the one hand, prevents the suppression of material removal

and abrasive during the processing. On the other hand, resin makes it impossible to study these areas, which can provide valuable information, such as the composition of minerals condensed from volcanic gas. An alternative method of sample preparation is to create fractures. Rocks can be broken with a geologist's hammer for this reason; however, this method does not provide the opportunity to select a fixed load for a series of samples or to control the shock propagation direction. In this process, the hammer also inevitably contacts the fracture surface, causing contamination, additional fractures, and surface damage. The fresh specimen surface can be obtained using a pendulum impact tester. Many studies have investigated sample destruction due to thermal, mechanical, electrical, and physical influences [6-11]; however, these works are primarily concerned with fracture initiation and propagation. Direct fracture surface examination by High-Resolution (HR) SEM has traditionally been used for industrial materials such as ceramics, composites, and alloys [1] but not for rocks. HR-SEM has a significant role in fractography due to three features of the instrument: high resolution, large depth of field, and the

ability to obtain chemical information via X-rays analysis [6]. Fracturing will occur predominantly along the weakest areas of a medium [12]; therefore, in basalt, fractures should pass through grain boundaries and pore spaces, thus preserving the 3D morphology of the rock's constituent mineral phases. Fracturing can also pass through submicron inclusions in macro crystals, which act as stress concentrators. Ideally, a fracturing method should add minimal artifacts to the sample and be reproducible. To address this, an Izod pendulum is used in this study to fracture samples under identical conditions. Using various basalt samples, we identify several types of submicron features in fracture surfaces that are fundamentally impossible to obtain on polished sections, and we also reveal the growth origin of zoning in rock-forming minerals in some cases.

1. Sample materials and analytical methods

The samples under study were selected after a preliminary investigation of basaltic lavas from the eruptions of 1941, 1975–1976, and 2012–2013 from Tolbachik (Kamchatka Peninsula, Russia) fissure zone (T) [13–15] and 2002, 2018, and 2019 from Etna (Italy) vents (E) [16–20]. The samples were previously studied in detail in both polished and thin sections [21]. In general, basalts comprise crystals of olivine, pyroxene, plagioclase, an amorphous volcanic glass phase, and accessory minerals in different proportions and contain pores [22].

The preliminary basalt samples used here were rectangular blocks of approximately 1×1×3 cm, which were determined to be free of pre-existing microcracks or other alterations based on optical microscopy inspection. During cutting the rock into blocks using a precision saw (ISOMET 4000), it was taken into account that the disturbance zone was at least 1 mm. In the proposed method, the pendulum hammer breaks the sample instantly in a selected area. Here, fractures were obtained using an Izod pendulum model Tinius Olsen IT504, which is a pendulum impact tester. The operating principle of this apparatus is based on a freely swinging pendulum impacting a sample held in a one-sided vice grip. The edge of destruction is determined by the height of the sample attachment in the vice. The machine allows one to vary the impact energy by selecting the mass of the load and its initial height, which determines the potential energy of the pendulum. Thus, this method ensures equal impact force and uniform sample destruction. The standard capacity range of the pendulum is from 2 J to 2,82 J; this can be increased to a maximum of 25 J, using different weight sets to achieve capacities of 5 J, 7,5 J, 15 J, and 25 J. The nature of the fracture in the sample material is associated with the brittleness, density, porosity and fracturing of the rock. The microstructure of a rock sample, such as the size and shape of mineral phases, the direction of crystal growth, the shape-preferred orientation of rock-forming minerals, and pre-existing microcracks, controls the process of crack initiation and propagation [23].

The fracture surfaces were coated with carbon using a Jeol JEE-4x vacuum evaporator in a dynamic tilting and rotating mode. The fractures were analyzed by SEM in secondary electron imaging (SEI) and backscattered electron imaging (BSE) modes. This study was performed using

a JEOL JSM-7001F SEM equipped with a field emission cathode and an Oxford X-Max 80mm² energy dispersive spectroscopy (EDS) spectrometer. The optimal operating parameters were an accelerating voltage of 10–25 kV, a beam current of 10^{–10} A, and a working distance of 10 mm. The BSE compositional contrast mode (COMPO) was used to obtain high-resolution images illustrating the mean atomic number contrast. The fracture surface and mineral micro-nanophase morphology were studied in BSE topographic contrast (TOPO) and SEI modes. The optimal conditions for diagnosing a sample's heterogeneous chemical composition are the absence of topographic contrast, a surface orientation perpendicular to the electron probe, and a homogeneous area with a diameter of 2–3 microns [3]. A specific workflow was introduced to analyze the submicron crystals: first, the EDS spectrum was recorded at several points within a crystal. The elemental composition of the submicron grains was determined by comparing a set of characteristic lines at the points of analysis of the grain under study and in adjacent or underlying minerals. Among the measured locations, the point with minimal characteristic X-ray line intensities of the elements of the surrounding matrix was selected. As the accelerating voltage decreases, the intensity of X-ray radiation from the chemical elements of the surrounding matrix decreases, and the relative intensity of X-ray radiation from the chemical elements of the sub-micron crystals increases. The fracture surface roughness degrades the COMPO image quality and reduces the X-ray lines' intensity; however, areas with suitable contrast and X-ray intensity can be identified by changing the sample orientation. Accordingly, a five-axis target holder was used to change the samples' orientation. It should be noted that analysis cannot be performed at the bottom of deep pores because of detector shadowing, but in such a case only the pore walls closest to the fracture surface are available for study. To ensure that the phase was not introduced during sample preparation, only those grains were selected for analysis that had reliable contacts with the surrounding perfectly faceted crystals of ortho-, clinopyroxene, plagioclase or glass matrix. Overall, the method proposed in this study represents a potentially effective technique for revealing additional features in SEM analyses of hard rocks and could be more broadly applied to overcome some of the limitations of conventional polished section analyses.

2. Results

The failure mechanism of basalt at room temperature is brittle [11]. On the fracture surface mineral grains are markedly angular and have excellent crystallographic faceting.

Important features of olivine formation in basalt were reflected in the different nature of the relief of its fracture surface (Fig. 1a). The crystal contains a clearly distinguished core and outer zone, which can be seen in the profile of the distribution of the main chemical elements (Fig. 1a). The stable intensity of the silicon line confirms the absence of topographic artifacts over the profile. If the surface of the scanned region is tilted, the analyzed point can be ensured to be horizontal using a five-axis electron microscope stage. Based on the profile scanning data, a change in forsterite content ($Fo = \text{Mg}/(\text{Mg}+\text{Fe}) \times 100 \%$) is

present in the outer zone. Forsterite content Fo is an important compositional indicator, used to assess the degree of evolution experienced by magmas, and calculate magma crystallization and mantle potential temperatures. The crystal core has a homogeneous composition, with a smooth, flat fracture surface. In contrast, the crystal rim exhibits a stepwise fracture pattern and the Fo% increases in this zone. The boundary between these areas is visible in the fracture topography and COMPO mode (Fig. 1a). However, in polished sections of such crystals, compositional heterogeneities appear more clearly (Fig. 1b). Thus, fracture topography can reduce the samples characterization capabilities of the COMPO mode, but at the same time it carries valuable information on fine grain properties.

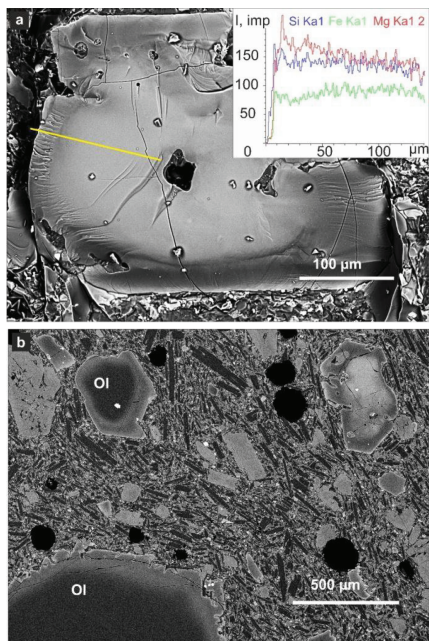


Fig. 1 Images of Tolbachik volcano basalts with large olivine crystals in BSE (COMPO) mode: a – fracture surface and the distribution of the main chemical elements in an olivine crystal (Ol: olivine). The inset shows the distribution of the characteristic line intensity of Si, Fe, Mg along the profile (yellow line) in the olivine crystal and b – polished section

1. ábra A Tolbachik vulkán bazaltjainak képei nagyméretű olivin kristályokkal, BSE (COMPO) üzemmódban: a – törési felület és a fő kémiai elemek eloszlása egy olivin kristályban (Ol: olivin). A belső kép a Si, Fe, Mg karakterisztikus vonalintenzitásának eloszlását mutatja a profil mentén (sárga vonal) az olivinkristályban; b – csiszolat

The polished surface (Fig. 2a) of the basalt samples sometimes exhibits some submicron-scale bright areas containing calcium and phosphorus. Based on the data obtained for this sample, the composition of the bright areas corresponds to apatite. An analysis of grains in open pores and on the fracture surface confirms the identification of this mineral as apatite. In one fracture, apatite is observed as needle-shaped hexagonal crystals (Fig. 2b, d) with a thickness on the order of one micron or less. Submicron crystals of apatite and orthopyroxene crystallized at the olivine–plagioclase boundary are also observed on the fracture surface (Fig. 2e). Apatite crystals of 1–3 μm size occur as inclusions in augite and plagioclase (Fig. 2f) much more commonly in the fractured sample compared to its polished counterpart. The bulk morphology of the submicron phases is also clearly visible on the fracture surface, thus making the identification of these mineral species more reliable.

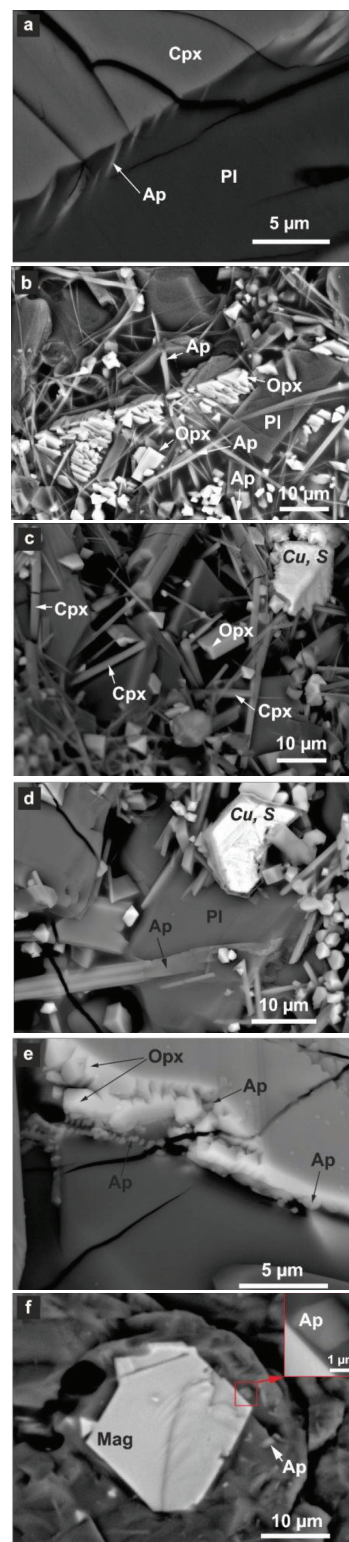


Fig. 2 Images of basalt samples in BSE (COMPO) mode: a – apatite on the polished section surface (E); b – needle-shaped apatite crystals on the fracture surface (E); c – elongated pyroxene crystals and chalcopyrite on the fracture surface (E); d – apatite and covellite on the fracture surface (E); e – apatite crystallizing on olivine on the fracture surface (T); and f – Ti-magnetite and apatite inclusions on the fracture surface in feldspar (T) (Ap: apatite; Cpx: clinopyroxene; Mag: magnetite; Opx: orthopyroxene; Pl: plagioclase)

2. ábra Bazaltminták képei BSE (COMPO) üzemmódban: a – apatit a csiszolat felszínén (E); b – tű alakú apatit kristályok a törési felszínen (E); c – megnyúlt piroxén kristályok és kalkopirit a törési felületen (E); d – apatit és kovelit a törési felületen (E); e – olivinen kristályosodó apatit a törési felszínen (T); f – Ti-magnetit és apatit zárványok a törési felületen, földpáthban (T). (Ap: apatit; Cpx: klinopiroxén; Mag: magnetit; Opx: ortopiroxén; Pl: plagioklász)

The fracture also clearly reveals larger (more than 10 μm in length) grains of apatite. Fig. 3a shows such a crystal in clinopyroxene. Fig. 3b demonstrates apatite in a titanomagnetite matrix. A visible gap between the phases can be explained by differential thermal expansion of the minerals. Such inclusions are retained in the matrix only if their size is larger than the open space in the matrix. Therefore, the lack of tight contact and adhesion between the phases can have consequences during thin or polished section preparation. Inclusions can easily fall out during the cutting, grinding, or polishing stages.

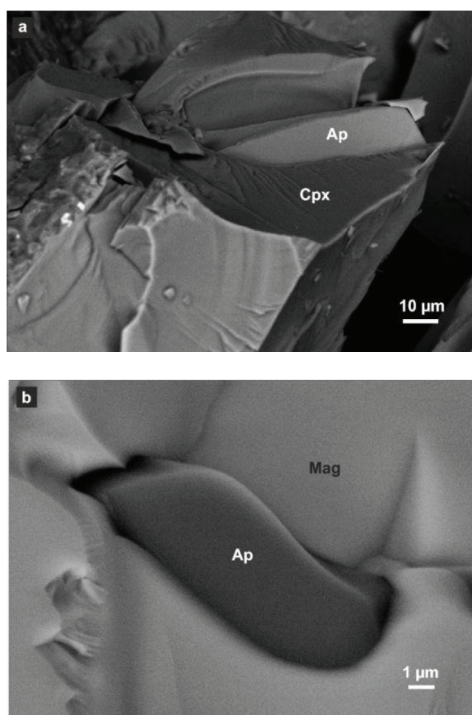


Fig. 3 Images of apatite found on the fracture surface in BSE (COMPO) mode: a – apatite in clinopyroxene (T); b – apatite in Ti-magnetite (T); (Ap: apatite; Cpx: clinopyroxene; Mag: magnetite)

3. ábra Törési felületen talált apatit képei BSE (COMPO) üzemmódban: a – apatit klinopiroxénben (T); b – apatit Ti-magnetitben (T). (Ap: apatit; Cpx: klinopiroxén; Mag: magnetit)

Many crystals of accessory minerals can be found on the fracture surface. For example, Fig. 2f shows well-faceted individual titanomagnetite crystals in feldspar. The morphological features of the micron and submicron pyroxene crystals and aggregates, and the oxides and sulfides of copper, zinc, iron, and nickel in lava samples from Etna and Tolbachik, are presented in Fig. 2b-f and 4a-f. Figure 4b shows nickel-containing chalcopyrite in a silicate melt. In a pore space of the Etna basaltic lava sample (2002 eruption), associations of elongated pyroxene crystals with 10 μm size chalcopyrite and covellite crystals are observed (Fig. 2c, d). Copper also occurs as an oxide, as well-faceted crystals of cuprite (Fig. 4c), and as micron-sized inclusions in olivine (Fig. 4d) and in the silicate matrix (Fig. 4f), as previously reported [24]. A micron-sized phase with a dominantly copper and nickel composition was found on an elongated columnar pyroxene crystal (Fig. 4e). As shown, the diversity of accessory minerals is much more representative and revealed more clearly on the fracture surfaces than on the polished ones.

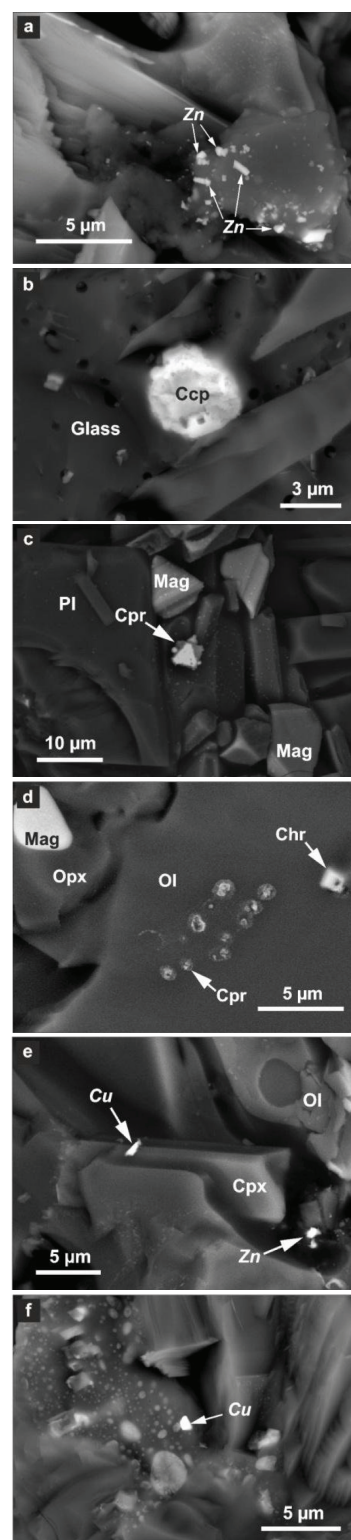


Fig. 4 Images of the fracture surface of basalts with accessory minerals in melt inclusions and pores in BSE (COMPO) mode: a – zinc in oxide form in silicate matrix (T); b – chalcopyrite with nickel admixture in a silicate melt (E); c – cuprite (T); d – cuprite in olivine (T); e – copper and nickel (left) + zinc (right) (T); f – copper in oxide form in a silicate matrix (T); (Ccp: chalcopyrite; Chr: chromite; Cpr: cuprite; Cpx: clinopyroxene; Mag: magnetite; Ol: olivine; Opx: orthopyroxene; Pl: plagioclase)

4. ábra Járulékos ásványokat tartalmazó bazalt törési felületének képei olvadákszárványokban és pórusokban, BSE (COMPO) üzemmódban: a – cink oxid formájában szilikát mátrixban (T); b – nikkel tartalmú kalkopirit szilikát olvadékban (E); c – kuprit (T); d – kuprit olivinben (T); e – réz és nikkel (balra) + cink (jobbra) (T); f – réz oxid formájában szilikát mátrixban (T). (Ccp: kalkopirit; Chr: kromit; Cpr: kuprit; Cpx: klinopiroxén; Mag: magnetit; Ol: olivin; Opx: ortopiroxén; Pl: plagioklász)

It is possible to find copper in its native form in the pore space due to the reducing environment of volcanic gases, such as sulfur dioxide (SO₂) and hydrogen sulfide (H₂S) [25]. Fig. 5 shows a phase with a high (92-94%) copper content on plagioclase.

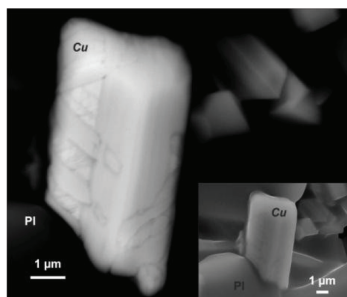


Fig. 5 Copper containing phase (Cu content according to EDS data is 92-94%) on plagioclase in BSE (COMPO) mode (T); (Pl: plagioclase). The inset shows the same area in SEI mode

5. ábra Réztartalmú fázis (a réztartalom az EDS adatok alapján 92-94%) plagioklázson, BSE (COMPO) üzemmódban (T). (Pl: plagioklász). A belső kép ugyanazt a területet mutatja SEI üzemmódban

3. Discussion

The chemical composition of the studied grains was determined after analyzing the images at different magnifications. Some zoning features are observed on the fracture surfaces of individual macro crystals. Zones with a significant change in average atomic number often exhibit differences in surface relief at the submicron scale. For example, the BSE (COMPO) images of olivine crystals from early melt crystallization exhibit an apparent direct zoning pattern represented by dark cores surrounded by bright rims, implying that the Fo% decreases towards the crystal rims [26]. Grains with direct zoning were previously studied based on compositional contrasts in polished sections [22]. Large crystals with reverse zoning were observed in basaltic lava crater facies. The COMPO mode shows a brighter crystal core surrounded by a dark rim, implying that the Fo% increases towards the crystal rim, representing reverse zoning of olivine [26]. At high resolution, the COMPO images reveal a thin zone between the core and the rim with a higher Fo% and the presence of nickel. The crystal's compositional variations were found to also be reflected in the fracture surface topography. The boundary in relief between the core and rim indicates a break in olivine crystallization; thus, the presence of a boundary in the fracture relief allows the post-growth diffusion model to be rejected for this zoning.

The morphology of the micron and submicron crystals is fully and clearly manifested on the fracture surface. This distinguishes a fracture surface from the polished surface of random cuts of crystals present in sections. The pores and inclusions are not filled with epoxy resin when fractured, thus allowing their composition to be studied at high magnification using lateral scanning. In lava samples from Etna and Tolbachik, the fracture surfaces expose numerous mineral phases containing copper, zinc, nickel, and iron in oxide and sulfide forms. Some of these mineral phases are accessory minerals in melt inclusions and pores. It is very difficult to ensure these submicron grains are on polished sample surfaces and even more difficult to determine their composition. Observing copper in various forms helps to determine the sample's formation

mechanism [27]. Direct observation of the crystal habit of copper-bearing minerals allows sulfur deficiency in the parent lava to be estimated. We interpret that sulfur was lost from the lava as a gas during the extrusion and crystallization of the samples in this study [28; 29]. The composition of the mineral phases found in the pores is consistent with the composition of the volcanic gases recorded during the eruption [25].

A generalized diagram comparing a polished surface and a fracture is shown in Fig. 6. The direction of crack propagation is determined by the presence of the nearest stress concentrators in the rock. For example, grain boundaries with poor adhesion due to the contamination between the phases, which significantly reduces their real contact area [30]. Also, the preferred paths for crack propagation are intracrystalline twinning and gliding planes, inclusions in crystals and other flaws. As shown, the chemical and morphological features of the grains present in the pores and fracture surfaces provide additional information on rock-forming conditions. Studying fracture surfaces does not allow precise determination of the chemical composition of the main rock-forming minerals; however, this approach nonetheless has several important advantages. The main advantage is the conservation of all submicron-sized grains in porous and macro-grain interfaces, which can then be qualitatively analyzed. In addition, this method also allows the interpretation of submicron inclusions in macro grains.

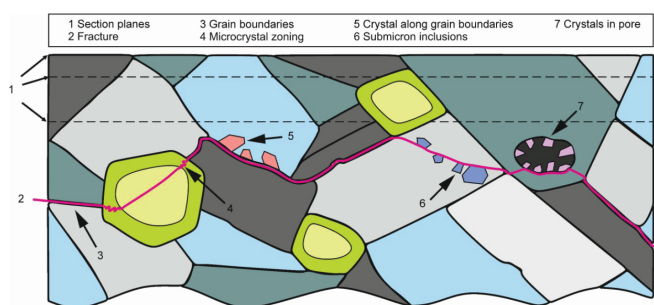


Fig. 6 Generalized diagram of the mineralogical features of the fracture propagation path through the crystallized area of a hard rock sample

6. ábra Általánosított diagram a repedés terjedési útvonalának ásványtani jellemzőiről egy kristályosodott kőzetminta területén keresztül

4. Conclusions

In this study, we reveal that investigating the fractured surface of basalt samples using HR-SEM has some crucial advantages compared to studying polished surfaces. As a direct result, sub-micron crystals of apatite, oxides and sulfides of copper, zinc, iron, and nickel were identified in lava samples from Etna and Tolbachik volcanoes. Minerals containing copper, zinc and nickel were revealed in most of the samples. Studies of fracture surfaces can also reveal microcrystal zoning, inclusions in macro crystals, and the morphology and composition of submicron crystals in pores and along grain boundaries. The results of this study show that olivine crystals exhibit changes in fracture relief at the boundary of zones with different compositions. Studying fracture surfaces allows submicron accessory minerals to be identified and the zoning of crystals of rock-forming minerals to be characterized in detail. Thus, the sample fracturing technique can be very useful in revealing accessory minerals in igneous and metamorphic rocks in addition to studying polished surfaces.

Data availability

The data are publicly available. Details regarding the data supporting the reported results can be found from the first author.

Competing interests

The authors declare no conflicts of interest.

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Advancing sustainability in construction: a review of supplementary cementitious materials and their environmental impact

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Abstract

This article provides a comprehensive overview of sustainable construction materials, with a focus on innovative alternatives to traditional cement. The study examines the use of calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash as partial replacements for cement in concrete production. The paper presents a detailed performance evaluation of concrete incorporating these materials, analyzing their effects on strength, durability, and workability. Technical guidelines for the optimal use of these sustainable alternatives are provided, including recommended replacement levels and mix design considerations. The review highlights the significant environmental benefits of these materials, such as reduced CO₂ emissions and the conservation of natural resources. Additionally, the paper explores the potential applications of these sustainable alternatives in various construction projects, addressing challenges and opportunities for their widespread adoption. This research contributes to the ongoing efforts to mitigate the environmental impact of the construction industry while maintaining high-performance standards.

Keywords: sustainable construction, calcined clay, recycled glass powder, recycled concrete aggregates, rice husk ash

Kulcsszavak: fenntartható építés, kalcinált agyag, újrahasznosított üvegpor, újrahasznosított beton adalékanyagok, rizshéj hamu

1. Introduction

The construction industry is confronted with significant environmental challenges due to the extensive use of concrete. This essential material for modern infrastructure is a major contributor to greenhouse gas emissions. As noted by [1], concrete is indispensable due to its versatility and structural integrity, but its environmental footprint cannot be ignored. This paper examines the environmental impact of concrete production, focusing on its contribution to global CO₂ emissions. Our research addresses the urgent need for mitigation strategies that balance environmental sustainability with the functional demands of construction.

Concrete is a composite material consisting of cement, water, and aggregates. Its unique properties, such as high compressive strength, durability, and adaptability, have established it as the cornerstone of infrastructure development [2]. However, these benefits come at a significant environmental cost. The cement industry, responsible for producing the binding agent in concrete, is a major emitter of CO₂, contributing approximately 8% of global emissions [3]. This figure highlights the critical need for sustainable alternatives and more efficient production methods to reduce the carbon footprint of this material.

Our study explores effective strategies to minimize the carbon emissions associated with concrete production without

compromising its structural performance. The investigation focuses on promising sustainable materials, such as calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash, which have been identified in previous studies as partial substitutes for traditional cement [3], [4], [5]. These materials are evaluated for their mechanical properties, durability, and environmental impact, with a focus on their performance in comparison to conventional concrete. Additionally, the technical and economic feasibility of scaling up these materials within the construction industry is analyzed, aligning with findings from [6], [7].

The hypothesis of this study is that integrating alternative materials and innovative production techniques can substantially reduce the environmental impact of concrete while maintaining or even enhancing its desirable properties. Prior research suggests that a combination of optimized mix designs, advanced curing techniques, and carbon capture technologies could enable a transition toward more sustainable concrete production [8].

The importance of this research extends beyond academic interest. With the global community striving to mitigate climate change, addressing the environmental impact of one of the most widely used construction materials is essential. Reducing CO₂ emissions from concrete production could

significantly contribute to international climate goals, such as those outlined in the Paris Agreement [9]. Furthermore, sustainable innovations in concrete production could conserve natural resources, promote circular economy practices, and foster the development of greener urban environments [10].

The subsequent sections of this paper delve deeper into the environmental challenges associated with concrete, assess the potential of sustainable materials, and evaluate their technical and economic viability. By presenting a comprehensive analysis, we aim to support ongoing efforts to revolutionize the concrete industry and promote the adoption of greener practices.

Despite these advancements, research gaps persist:

1. **Standardization:** The absence of a standardized approach makes it difficult to accurately compare the environmental impact of different concrete mixes and products. This complicates decision-making for designers, engineers, and policymakers who aim to select the most sustainable options for their projects. The lack of standardization can act as a barrier to the widespread adoption of low-carbon concrete alternatives [11]. Without clear, universally accepted methods for measuring and verifying carbon reductions, there may be hesitation in specifying or approving innovative, more sustainable concrete mixes.
2. **Methodology:** Without a unified methodology, different manufacturers and researchers may use varying approaches to calculate and report the carbon footprint of their concrete products [12]. This can lead to inconsistencies in environmental product declarations (EPDs) and make it challenging for stakeholders to make informed decisions.
3. **Optimization:** Existing models fail to optimize concrete mixtures holistically for sustainability, cost, and performance [13]. Advanced algorithms are being employed to model complex relationships between mixture components and concrete properties. For example, [14] developed a multi-objective optimization model using a back propagation neural network (BPNN) to predict concrete properties. However, the long-term performance uncertainty persists. Studies on the long-term durability of sustainable concrete in diverse environmental conditions remain limited, making it challenging to incorporate these factors into optimization models [15].
4. **Long-term performance:** Studies on the long-term durability of sustainable concrete in diverse environmental conditions remain limited [8]. There is a necessity to develop more comprehensive datasets that include a wider range of materials and mixture designs [14].

2. Methodology

A total of 153 papers were initially identified through database searches. After removing duplicates and screening titles for relevance, 67 studies were selected for the final comprehensive review.

This literature review employed a systematic approach to identify, evaluate, and synthesize relevant research on sustainable construction materials and their environmental impact. The methodology followed these key steps:

▪ Search strategy

1. Database selection: We conducted searches in major academic databases including Web of Science, Scopus, and Google Scholar.
2. Search terms: Keywords and phrases used included “sustainable construction materials,” “supplementary cementitious materials,” “environmental impact of concrete,” “calcined clay,” “recycled glass powder,” “recycled concrete aggregates,” and “rice husk ash.”
3. Time frame: The search focused on literature published between 2015 and 2025, with emphasis on the most recent studies (2020-2025).

▪ Selection criteria

Inclusion criteria:

- Peer-reviewed journal articles and conference proceedings
- Studies focusing on supplementary cementitious materials and their environmental impact
- Research evaluating the performance of sustainable concrete materials
- Lifecycle assessments of sustainable construction materials
- Studies published in English

Exclusion criteria:

- Non-peer-reviewed articles, opinion pieces, and commercial reports
- Studies not directly related to sustainable construction materials
- Research focusing solely on traditional cement without sustainable alternatives

▪ Screening process

1. Initial screening: Titles and abstracts were reviewed to determine relevance based on the inclusion and exclusion criteria.
2. Full-text review: Selected articles underwent a comprehensive full-text review to ensure alignment with the research objectives.
3. Quality assessment: Studies were evaluated for methodological rigor, sample size, and relevance of findings.

▪ Data extraction and synthesis

1. Key information was extracted from selected studies, including:
 - Material properties and performance characteristics.
 - Environmental impact assessments.
 - Experimental methodologies.
 - Key findings and conclusions.
2. Data was synthesized thematically, focusing on:
 - Types of sustainable materials.
 - Environmental benefits.
 - Performance comparisons with traditional materials.
 - Challenges and limitations in implementation.

■ Analysis and interpretation

1. Comparative analysis of different sustainable materials was conducted to identify trends and patterns.
2. Findings were interpreted in the context of current construction industry practices and environmental goals.
3. Gaps in current research were identified to suggest directions for future studies.

This systematic approach ensured a comprehensive and unbiased review of the current state of knowledge regarding sustainable construction materials and their environmental impact [16], [17], [18].

3. The Environmental impact of concrete

[19] emphasize that current methodologies for calculating the carbon footprint of construction materials lack standardization, which complicates the assessment of greenhouse gas (GHG) emissions. They highlight deficiencies in global databases, which are often limited in scope and availability, and recommend that GHG emission assessments should adopt case-specific approaches, considering factors such as structure location, transportation distances, and energy sources, which vary between regions.

The primary source of CO₂ emissions in cement production stems from calcination, the chemical reaction occurring when limestone (CaCO₃) is heated in a kiln. This reaction produces lime (CaO) and releases CO₂ as a byproduct, a process responsible for roughly 60% of cement-related CO₂ emissions [10]. Additionally, the energy required to power kilns, predominantly derived from fossil fuels, accounts for another 30–40% of emissions [8].

Concrete's environmental impact extends beyond the production phase. Factors such as transportation, maintenance, and demolition contribute significantly to its carbon footprint. For example, [20] notes that transportation of raw materials and finished products can add up to 10% of the total embodied carbon in concrete. Furthermore, improper disposal of construction waste exacerbates environmental degradation, with demolition generating particulate matter and contributing to air pollution [3].

4. Enhanced methodology for sustainable construction materials research

To address existing research gaps, future studies must adopt a robust, holistic methodology that extends evaluation periods to 180 or 365 days to capture delayed strength development [26], while employing accelerated aging techniques to simulate long-term durability [27]. The scope of materials should be broadened to include synergistic ternary blends and low-carbon alternatives like LC3 [28], [29], tested under diverse environmental stressors such as freeze-thaw cycles and chloride exposure [30], [31]. Advanced microstructural analysis using 3D X-ray CT, XPS, NMR, and SEM is critical for understanding pore structure and chemical reactivity [32], [33], [34], [43], [44]. These experimental insights must be integrated with comprehensive lifecycle assessments (LCA) that account for regional transport

and climatic variations [35], [36], [37], [38], and optimized using machine learning algorithms and sensitivity analyses [39], [40]. Finally, validating these findings through large-scale field trials and economic feasibility studies is essential to ensure practical scalability and industry adoption [41], [42], [45], [46].

5. Advantages to using sustainable materials

The environmental benefits of using sustainable materials in concrete production compared to traditional methods are significant and multifaceted. A comprehensive analysis of these benefits, supported by lifecycle assessments, reveals the potential for substantial reductions in environmental impact across various stages of concrete production and use.

This analysis expands on the environmental benefits of using sustainable materials in concrete production compared to traditional methods, incorporating lifecycle assessments for various materials discussed in recent studies.

Reduced carbon footprint

One of the most significant environmental benefits of using sustainable materials in concrete is the reduction in carbon dioxide (CO₂) emissions. The use of sustainable materials in concrete production significantly reduces CO₂ emissions compared to traditional Portland cement concrete. A study on the effect of fly ash on lifecycle CO₂ assessment of concrete structures found that the lifecycle CO₂ amount decreases with increasing fly ash substitution up to 20% [47]. This reduction is primarily due to the lower energy requirements and reduced clinker content in cement production when supplementary cementitious materials (SCMs) are used. Concrete with 50% fly ash replacement and 10% effective microorganism (EM) solution showed approximately 49.3% lower carbon dioxide emissions compared to conventional concrete [48].

Lifecycle assessment of alkali-activated cement concrete revealed lower environmental impact compared to Portland cement concrete, despite some emissions from alkali activator production [49].

Resource conservation and waste reduction

The use of waste materials and industrial by-products as SCMs contributes to resource conservation by reducing the demand for virgin materials. For instance, the incorporation of recycled concrete aggregate (RCA) and recycled glass in concrete mixtures helps conserve natural aggregates and reduces the environmental impact associated with their extraction [50], [51]. A study on olive stone waste and crushed glass in concrete mixtures demonstrated that these materials could successfully replace up to 40% of natural aggregates, leading to reduced resource consumption [50].

Utilizing industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and ferrochrome slag in concrete production helps divert these materials from landfills. This not only reduces waste but also mitigates the environmental impacts associated with waste disposal. A comprehensive review of GGBS in concrete production highlighted its potential to sharply reduce the amount of industrial waste disposed of in lakes and landfills [52].

Sustainable materials in concrete production contribute to resource conservation and waste reduction:

- Recycled concrete aggregate (RCA): The use of RCA in concrete mixtures helps conserve natural aggregates and reduces the environmental impact of extraction. A lifecycle assessment study showed that concrete with RCA has a lower environmental impact compared to conventional concrete [53].
- Industrial by-products: Utilizing fly ash, ground granulated blast furnace slag (GGBS), and other industrial by-products in concrete production diverts these materials from landfills, reducing waste and associated environmental impacts [52].

Energy efficiency

The production of sustainable concrete often requires less energy compared to traditional methods. For example, the use of alkali-activated cement, which utilizes industrial by-products like fly ash and GGBS, can significantly reduce the energy-intensive processes associated with Portland cement production [53]. Sustainable concrete production often requires less energy compared to traditional methods.

Alkali-activated cement: While the production of alkali activators contributes some emissions, the overall energy requirements are lower compared to Portland cement production [54].

Lifecycle assessment

Lifecycle assessments (LCA) provide a holistic view of the environmental impacts of sustainable concrete materials. A study on the lifecycle and multi-criteria decision-making for high strength recycled aggregate concrete revealed that the third generation of recycled concrete offers a more favorable alternative with lower environmental impact compared to first or second-generation recycled concrete [49].

Another LCA study on alkali-activated cement concrete demonstrated that while the production of alkali activators contributes to some emissions, the overall environmental impact is still lower compared to traditional Portland cement concrete [55].

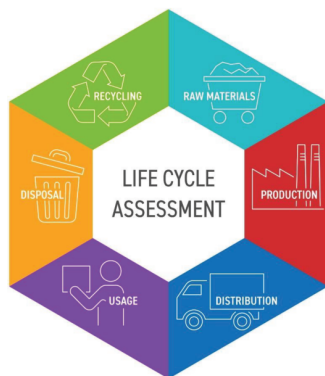


Fig. 1 Different stages considered in a comprehensive lifecycle assessment of sustainable concrete materials. [19][35][36]

1. ábra Fenntartható betonanyagok átfogó életciklus-elemzése során figyelembe vett különböző szakaszok

1. Fly ash:

Reduces lifecycle CO₂ emissions of concrete structures by up to 20% when used as a cement replacement [47]. Fly ash also

improves durability and reduces the need for frequent repairs, extending the structure's lifecycle [52].

2. Recycled concrete aggregate (RCA):

Lifecycle and multi-criteria decision-making analysis showed that third-generation concrete with RCA offers a more favorable alternative with lower environmental impact [55]. RCA concrete also reduces the demand for virgin materials and associated extraction impacts [51]

3. Alkali-activated cement:

Lifecycle assessment reveals lower overall environmental impact compared to Portland cement concrete[49]. Alkali-Activated Cement utilizes industrial by-products, reducing waste and resource consumption [49].

4. Biomass wood ash:

Biomass wood ash: A cradle-to-gate lifecycle assessment of alkali-activated mortar using biomass wood ash showed less environmental impact compared to traditional Portland cement mortar [56]. Its effective in using waste materials from biomass fuel production [57].

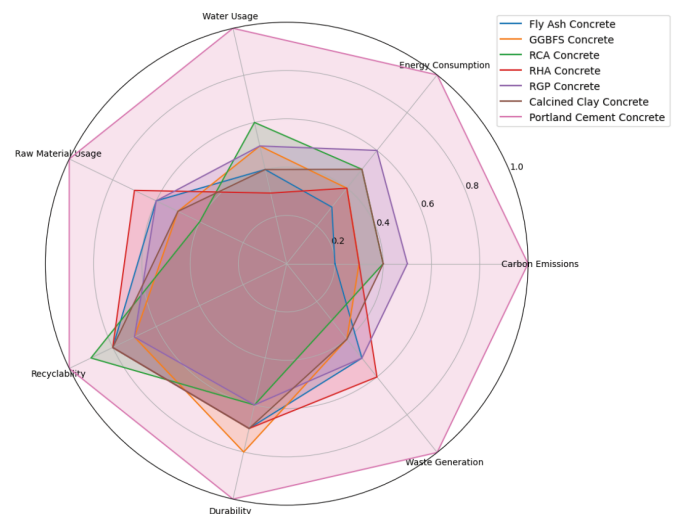


Fig. 2 Environmental impact radar chart for different concrete types. [28][43][47][53][55][62]

2. ábra Különböző betontípusok környezeti hatásának radardiagramja

5. Dune sand and fiber-reinforced concrete:

Utilizes locally available materials, potentially reducing transportation-related emissions [58]. It improves concrete durability, extending the lifecycle of structures [58].

6. Secondary waste from incineration plants:

Using fly ash and bottom ash from municipal solid waste incineration in concrete decreases CO₂ emissions and abiotic depletion compared to traditional concrete [50]. Using this type of waste contributes to circular economy principles and sustainable development goals.

A radar chart would visually represent these concrete types using different colors and markers, with the area covered by each type indicating its overall environmental impact. Smaller areas represent lower environmental impacts.

Long-term durability and performance

Sustainable concrete materials often exhibit improved durability, which extends the lifecycle of structures and reduces the need for frequent repairs or replacements. For instance, the incorporation of fly ash and silica fume in high-strength concrete has been shown to enhance long-term performance and durability [59].

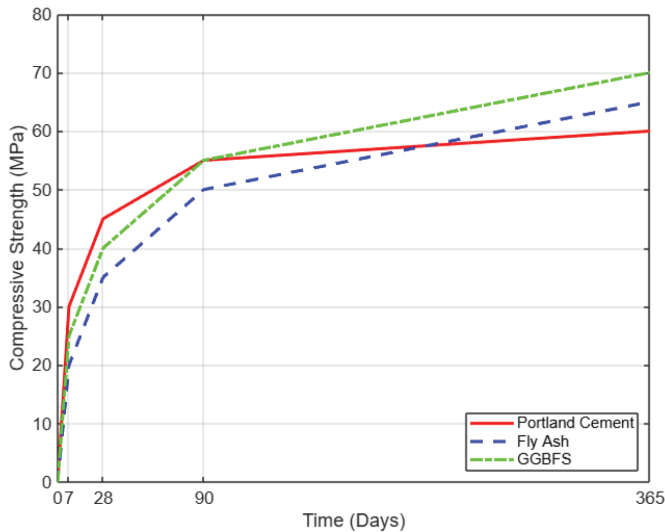


Fig. 3 Strength development of concrete with different SCMs. [26][62][63]
3. ábra Beton szilárdságfejlődése különböző SCM-ek alkalmazásával

Compressive strength development over time. This graph illustrates how SCMs like fly ash may have slower early strength development but can match or exceed traditional concrete strength in the long term.

Carbon sequestration

Recent advancements in carbon-absorbing concrete technologies offer the potential for concrete to actively sequester CO₂ during its lifetime. A systematic review of carbon-absorbing concrete technologies highlighted the use of materials such as fly ash, graphene oxide, and blast furnace slag to enhance concrete's carbon absorption capabilities [60]

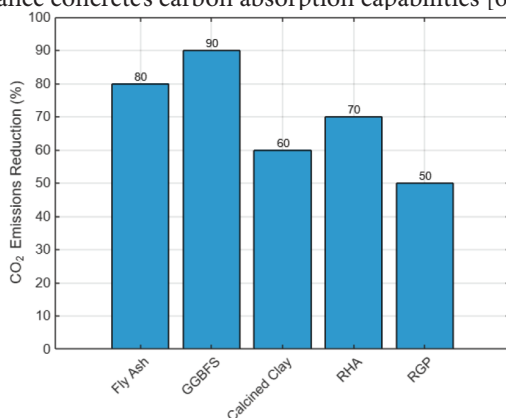


Fig. 4 Maximum potential CO₂ emission reductions achievable through high-volume substitution or alkali-activation of SCMs compared to traditional portland cement. [28][47][48][49].
4. ábra Nagyarányú SCM helyettesítéssel vagy azok lúgos aktiválásával elérhető maximális potenciális CO₂-kibocsátás-csökkentés a hagyományos Portlandcemenethez képest

In conclusion, the use of sustainable materials in concrete production offers substantial environmental benefits compared to traditional methods. These benefits include reduced CO₂ emissions, conservation of natural resources, waste reduction, improved energy efficiency, and potential carbon sequestration. Lifecycle assessments consistently demonstrate the lower environmental impact of sustainable concrete materials across their production, use, and end-of-life stages. As research in this field continues to advance, the potential for even greater environmental benefits through innovative sustainable concrete technologies becomes increasingly promising.

4. Research directions

Traditional materials with a sustainable twist

Fly ash: a sustainable alternative

Fly ash, a byproduct of coal combustion in thermal power plants, has gained prominence in sustainable concrete production. Its use significantly reduces CO₂ emissions by decreasing cement consumption and repurposing waste materials. Studies confirm that fly ash enhances concrete's durability by reducing permeability, thereby increasing resistance to chloride and sulfate attacks [62], [63]. Despite initial reductions in early-age strength, long-term strength development in fly ash concrete (FAC) often matches or surpasses conventional concrete as the curing period increases [63]. The pozzolanic reaction of fly ash generates additional calcium silicate hydrate (C-S-H) gels, contributing to strength development and reducing water demand in concrete mixtures [62].

SCM	Key properties	Environment benefits
Fly ash	- Enhances durability. - Reduces permeability. - Improves resistance to chloride and sulfate attacks. - Contributes to long-term strength development.	- Reduces CO₂ emissions. - Decreases cement consumption. - Repurposes waste materials. - Reduces water demand in concrete mixtures.

Table 1 Key properties and environmental benefits of fly ash
1. táblázat A pernye főbb tulajdonságai és környezeti előnyei

Blast furnace slag: transforming waste into resource

Blast furnace slag, a byproduct of iron manufacturing, is increasingly used as a partial cement replacement due to its beneficial properties. Ground Granulated Blast Furnace Slag (GGBFS) improves compressive strength, durability, and resistance to chemical attacks, effectively reducing the risk of reinforcement corrosion in concrete [62]. Research indicates that replacing up to 50% of Portland cement with GGBFS can reduce the carbon footprint of concrete while extending setting times, thus enhancing workability. For example, replacement levels of 40–60% increase setting times by approximately one hour, providing a practical solution for hot climates [62].

SCM	Key properties	Environment benefits
Ground granulated blast furnace slag (GGBFS)	- Improves compressive strength. - Enhances durability. - Increases resistance to chemical attacks. - Extends setting times.	- Reduces carbon footprint. - Repurposes industrial waste. - Enhances workability.

Table 2 Key properties and environmental benefits of ground granulated blast furnace slag (GGBFS)
2. táblázat Az őrlött granulált kohósalak (GGBFS) főbb tulajdonságai és környezeti előnyei

Innovative materials paving the way

Rice husk ash: a silica-rich supplement

Rice husk ash (RHA), a byproduct of burning rice husks, contains 80–95% silica and demonstrates significant pozzolanic activity when burned under controlled conditions [62]. Its inclusion in concrete reduces permeability, mitigates autogenous shrinkage, and improves durability, particularly in high-performance concrete [43]. Studies have shown that replacing 10% of cement with RHA increases compressive strength by approximately 7% at 90 days compared to conventional concrete, showcasing its potential for long-term performance enhancement .The incorporation of sustainable materials like RHA leads to a denser microstructure and enhanced pozzolanic reaction, contributing to improved long-term strength and durability. These findings align with recent studies by [64] and [44], which reported similar benefits of using supplementary cementitious materials [33], [65]. A 20% replacement of cement with RHA exhibits a compressive strength increase of 5–10% after 90 days, compared to control samples, corroborating [64].

SCM	Key properties	Environment benefits
Rice husk ash (RHA)	- High silica content (80-95%). - Significant pozzolanic activity. - Reduces permeability. - Mitigates autogenous shrinkage.	- Repurposes agricultural waste. - Improves long-term performance. - Enhances durability.

Table 3 Key properties and environmental benefits of rice husk ash (RHA)
 3. táblázat A rizshéj hamu (RHA) főbb tulajdonságai és környezeti előnyei

SCM	Key properties	Environment benefits
Recycled glass powder (RGP)	- Exhibits pozzolanic properties. - Contributes to higher compressive strength. - Improves durability under freeze-thaw conditions.	- Utilizes waste glass. - Reduces cement consumption. - Enhances microstructure of concrete.

Table 4 Key properties and environmental benefits of recycled glass powder (RGP)
 4. táblázat Az újrahasznosított üvegpór (RGP) főbb tulajdonságai és környezeti előnyei

Recycled glass powder: harnessing waste glass

Recycled glass powder (RGP), derived from waste glass, offers an environmentally friendly option for partial cement replacement. Its pozzolanic properties contribute to higher compressive strength and improved durability, particularly under freeze-thaw conditions. [43] demonstrated a 25% increase in compressive strength at 28 days with 20% cement replacement by RGP. Additionally, glass flour exhibits reactivity with cement matrices, enhancing the microstructure and sealing potential of fiber-reinforced concrete composites [64].

SCM	Key properties	Environment benefits
Calcined clay	- Exhibits pozzolanic properties - Enhances strength and durability	- Reduces cement-related carbon emissions - Widely available and accessible - Offers scalable solution for low-carbon cement production

Table 5 Key properties and environmental benefits of calcined clay.
 5. táblázat A kalcinált agyag főbb tulajdonságai és környezeti előnyei

Calcined clay: a widely available solution

Calcined clay, produced by heating natural clay, serves as a scalable and effective replacement for Portland cement. Its pozzolanic properties enhance strength and durability while

reducing cement-related carbon emissions by up to 50% when used as a replacement material [65]. With its abundance and accessibility, calcined clay offers a practical solution for low-carbon cement production globally [33].

7. Challenges in Hungary

Hungary’s construction industry is at a pivotal moment, grappling with the dual imperatives of meeting escalating infrastructure demands and adopting sustainable practices. As noted by recent studies on regional infrastructure trends, Hungary’s rapid expansion of projects, particularly in railway construction, has significantly heightened the demand for construction materials, such as crushed stone [66] This surge, driven by national and EU-funded initiatives, has overburdened supply chains, resulting in logistical bottlenecks and material shortages. With domestic production capacity constrained, effective resource management has emerged as a critical factor for ensuring project continuity and aligning with sustainability objectives [68].

Crushed stone, a foundational material in infrastructure development, epitomizes the resource challenges Hungary is experiencing. Domestic quarries are increasingly unable to satisfy the annual demand for railway ballast, which is estimated at approximately 192,000 tons [67]. This deficiency has necessitated higher reliance on imports, further emphasizing the urgency of identifying sustainable and locally sourced alternatives. Moreover, Hungary’s geological characteristics impose limitations on the availability of high-quality stone suitable for construction, as highlighted [69], making material sustainability an urgent priority.

To mitigate these challenges, Hungary is exploring sustainable material solutions, particularly the integration of recycled concrete aggregates (RCA). Research by [70] demonstrates that replacing up to 30% of natural aggregates with RCA yields mechanical properties comparable to those of traditional concrete, thereby offering a dual advantage of alleviating resource scarcity and reducing construction waste. Such findings align with global calls for circular economy models within construction [71].

The regulatory landscape in Hungary is gradually adapting to support these sustainability efforts. The introduction of the Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024 incorporates Prevention through Design (PtD) principles, emphasizing safety and sustainability across the construction lifecycle [72]. However, as highlighted in industry reports, awareness and compliance with these regulations remain limited, requiring targeted outreach and training initiatives.

Technological innovations are also playing a central role in Hungary’s efforts to transition toward sustainable practices. The adoption of Geographic Information System (GIS) modeling for transportation logistics exemplifies this trend. According to [73], GIS-based analyses have proven effective in optimizing material transport routes, thereby reducing costs and environmental impacts. This technology enables more efficient resource allocation and enhances decision-making related to local material sourcing.

Despite these promising developments, challenges persist. The integration of recycled materials and alternative aggregates is often constrained by concerns over quality control, performance

consistency, and industry acceptance [74]. Furthermore, the potential of locally abundant resources, such as volcanic tuff, to serve as sustainable alternatives in construction remains underexplored, warranting further research and development [75].

Recommendations for advancing sustainable construction in Hungary

- 1. **Enhancing the regulatory framework:** Strengthening regulations to explicitly promote sustainability is essential. Setting mandatory targets for recycled material use in public projects and incentivizing private developers to exceed these targets can accelerate the adoption of sustainable practices. Implementing comprehensive green building codes, addressing energy efficiency, water conservation, and material sustainability, aligns with best practices observed in leading EU countries [76].
- 2. **Investing in research and development:** Increasing funding for research into sustainable materials, particularly locally available options such as volcanic tuff, is crucial. Collaborative efforts between academic institutions, government agencies, and private sectors should aim to refine material performance and improve practical applications [77].
- 3. **Optimizing supply chain management:** Advanced logistics systems, supported by GIS technology, offer significant potential for enhancing the transportation and distribution of construction materials. A national database of construction material resources, as suggested [78], could facilitate better planning and resource allocation, minimizing environmental impact and reducing costs.
- 4. **Promoting education and training:** Comprehensive training programs for industry professionals are critical for addressing gaps in awareness and understanding of sustainable practices. Mandatory continuing education on sustainable construction methods, as recommended by [72], could ensure consistent adoption across the sector.
- 5. **Encouraging circular economy principles:** Incentivizing the reuse and recycling of construction and demolition waste is essential for achieving sustainability. Policies such as tax incentives for high recovery rates and penalties for excessive waste generation align with EU circular economy directives [79].
- 6. **Fostering international collaboration:** Strengthening partnerships with EU member states and international organizations can facilitate the exchange of best practices and technologies. Collaborative research projects and professional exchange programs can further enrich Hungary's capabilities in sustainable construction [80].

Implementing these recommendations will require overcoming entrenched challenges, including resistance from traditional industry players, the upfront costs of transitioning to new technologies, and significant investment in education and infrastructure. Nevertheless, the long-term benefits – such as reduced environmental impact, enhanced resource efficiency, and improved economic competitiveness – underscore the importance of pursuing a sustainable construction agenda in Hungary.

As Hungary navigates these complexities, balancing immediate infrastructure needs with long-term environmental and economic priorities is paramount. Leveraging its unique geological resources, adopting innovative technologies, and fostering a culture of sustainability within the construction

industry will position Hungary as a leader in sustainable development within Central Europe.

Recent developments and future outlook

Research on industrial by-products such as coal fly ash has revealed significant potential for their application in road construction and maintenance. A 2024 study highlighted the use of fly ash as filler in asphalt mixtures and cement, demonstrating Hungary's progress in repurposing industrial waste [81]. Comparative insights from international contexts, such as sustainable construction practices in Bangkok, underscore the importance of regulatory influence and stakeholder commitment in driving sustainability [80].

8. Conclusion

This comprehensive review has highlighted the significant potential of supplementary cementitious materials (SCMs) in advancing sustainability within the construction industry. The integration of materials such as calcined clay, recycled glass powder, recycled concrete aggregates, and rice husk ash as partial replacements for traditional cement has demonstrated promising results in reducing the environmental impact of concrete production while maintaining or even enhancing its performance characteristics. Key findings from this review include:

- 1. Substantial reductions in CO₂ emissions associated with concrete production through the use of SCMs.
- 2. Improved durability and long-term performance of concrete incorporating these sustainable alternatives.
- 3. Conservation of natural resources and reduction of waste through the use of recycled and by-product materials.
- 4. Potential for carbon sequestration in certain innovative concrete technologies.

However, challenges remain in the widespread adoption of these materials, including the need for standardization, optimization of mix designs, and scaling up of implementation. Future research should focus on:

- 1. Long-term performance studies under diverse environmental conditions.
- 2. Development of comprehensive lifecycle assessment models specific to different regions and applications.
- 3. Economic feasibility studies to encourage industry adoption.
- 4. Further exploration of novel materials and technologies for carbon-negative concrete production.

Property/ Benefit	Fly ash	GGBFS	RHA	RGP	Calcined clay
Strength enhancement	✓	✓	✓	✓	✓
Durability improvement	✓	✓	✓	✓	✓
Permeability reduction	✓	-	✓	-	-
Chemical resistance	✓	✓	-	-	-
CO ₂ emission reduction	✓	✓	✓	✓	✓
Waste material utilization	✓	✓	✓	✓	-
Cement consumption reduction	✓	✓	✓	✓	✓
Workability enhancement	✓	✓	-	-	-
Long-term performance	✓	-	✓	-	-
Wide availability	-	-	✓	-	✓

Table 6 Comparative summary of properties and environmental benefits across different supplementary cementitious materials (SCMs)
6. táblázat A különböző betonkiegészítő anyagok (SCM-ek) tulajdonságainak és környezeti előnyeinek összehasonlító összefoglalása

By addressing these challenges and continuing to innovate, the construction industry can significantly reduce its environmental footprint while meeting the growing global demand for infrastructure development.

Note: A checkmark (✓) indicates that the SCM exhibits the property or provides the benefit. A dash (-) indicates that the property or benefit was not specifically mentioned for that SCM in the provided information.

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Punching shear strengthening of the flat slab using SIFCON

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Abstract

Punching shear failure in flat slabs remains one of the most critical issues in reinforced concrete structures due to its sudden and brittle nature. This research investigates the potential of using Slurry Infiltrated Fiber Concrete (SIFCON) as an alternative to traditional punching shear reinforcement in flat slabs cast from normal strength concrete (NSC). The fiber type was hooked-end steel fiber with a fraction volume of 6%. Five square flat slab specimens were cast; the first specimen was cast using NSC. Four of them were reinforced with maximum flexural steel to ensure failure by punching shear. In two of these slabs, SIFCON was used as a whole slab, but since it is expensive to use SIFCON for entire slabs, in others, SIFCON was used partially over an extended area in a form similar to a cross-shaped shear reinforcement and full or partial depth to improve the capacity to punching shear. The data demonstrate that SIFCON, when applied strategically, is a highly effective material for increasing punching shear capacity and improving post-punching behavior and ductility. Providing a realistic alternative to standard reinforcement approaches.

Keywords: flat slab, Slurry Infiltrated Fiber Concrete, punching shear, steel fibers, post-punching behavior

Kulcsszavak: síkfödém, cementhabarccsal injektált szálerősítésű beton (SIFCON), átszűrődási nyírás

1. Introduction

Reinforced concrete flat slabs are increasingly favored in modern construction. By eliminating down-stand beams, the system relies on a simple, level formwork deck, streamlining site operations and accelerating the build. In multi-story projects, the reduced structural depth allows additional floors to be fitted within the same overall height. This efficiency cuts the quantity of façade materials, partition walls, and the length of mechanical, electrical, and plumbing runs, yielding notable savings in both resources and cost [1].

The main weakness of this type of roof is its failure with punching shear, as when making flat slabs using normal strength concrete (NSC), it is brittle and prone to punching shear failure, which occurs around columns at specific distances. Engineers have outlined several ways to raise the punching shear strength of flat slabs made with NSC. These include thickening the slab, adding column capitals, incorporating drop panels, placing additional shear reinforcement, and introducing advanced materials such as fiber-reinforced polymer (FRP) [2-4].

The cost and constructional intricacy of conventional strengthening techniques can, in many practical situations, offset the principal advantages of flat slab systems. Consequently, recent research has turned toward material solutions that increase punching shear capacity while preserving ease of execution. Other methods have been used to strengthen NSC flat slabs, using partially special types of concrete, some of which are high-strength concrete (HSC) or fiber-reinforced concrete (FRC). These concretes have been used by previous researchers in various ways and placed in different areas, depths, and shapes in flat slabs to perform their intended

function. They have led to a noticeable improvement in the shear capacity of flat slabs [5-11]. In Slurry Infiltrated Fiber Concrete (SIFCON), the volume fraction of fibers is usually high, roughly 4% to 20% [12]. Ordinary FRC, by comparison, rarely exceeds about 2% fiber because it is mixed directly with cement, sand, and coarse aggregate, and workability quickly deteriorates [13]. SIFCON sidesteps this issue through a different production method: dense fibers are placed in the mold first, and a highly slurry mortar is then infiltrated to occupy the gaps between fibers. This manufacturing sequence yields a composite distinguished by exceptional toughness and markedly enhanced compressive, tensile, shear, and flexural strengths [14].

Published work on how best to employ SIFCON for upgrading reinforced concrete flat slabs is still sparse. In the present investigation, flat slab specimens were cast in which NSC was replaced, either wholly or partially, by SIFCON. Also, SIFCON was used partially over an extended area in a form similar to a cross-shaped shear reinforcement and full or partial depth to improve the resistance to punching shear. The study gauges how SIFCON replacement alters the slab's resistance to punching shear by comparing these configurations.

2. Experimental work

2.1 Materials and mix design

The materials composition adopted in this study, combining SIFCON and NCS, is detailed in *Table 1*. The binding materials comprise Portland cement type CEM I (42.5) along with silica fume. Normal quartz sand with a maximum particle size of

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1 mm and 4 mm is used as a fine aggregate for SIFCON and NSC, respectively. 4/8 mm and 8/16 mm are used as coarse aggregates for NSC. Fig. 1 shows the particle size distribution of aggregates. To ensure proper workability of the SIFCON mix, the high-range water-reducing admixture BASF Master Builders Solutions was incorporated. Flexural reinforcement was provided according to the specifications of ACI 318-19 [15], employing Ø10 mm deformed bars positioned on the tension side of the slabs to promote punching shear as the governing failure mode. In this investigation, steel fibers were hooked-end with a volume fraction of 6%. The type of fiber employed is illustrated in Fig. 2, while Table 2 presents its technical characteristics as reported by the manufacturer.

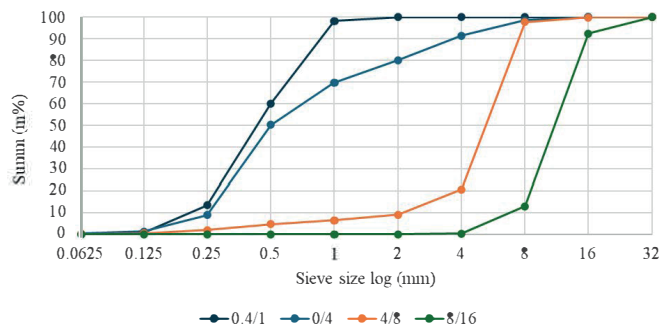


Fig. 1 Particle size distribution of aggregates
1. ábra Adalékanyagok szemmegoszlási görbéje

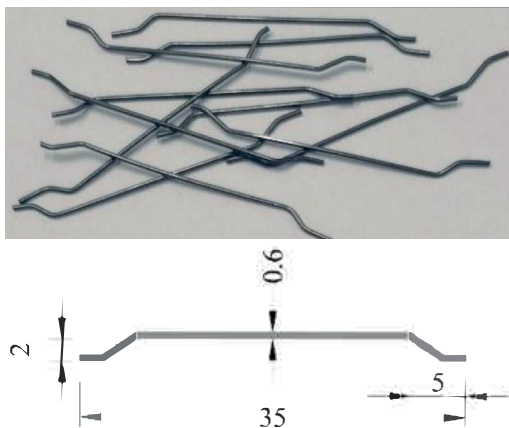


Fig. 2 Hooked-end steel fiber, the dimensions are in millimeters
2. ábra Visszahajlított végű acélszál, a méretek milliméterben értendők

Cement (kg/m ³)	Sand (0.4-1) mm (kg/m ³)	Sand (1-4) mm (kg/m ³)	Coarse agg. (kg/m ³) (4-8) mm (8-16) mm	Silica fume kg/m ³ 10% rep.	Steel fiber %	w/b or w/c ratio	SP (by wt. of binder) %
370	–	924	462	462	–	50%	–
873	970	–	–	–	97	6	30%

Table 1 NSC and SIFCON optimal mixing proportions for 1 m³
1. táblázat NSC és SIFCON optimális keverési arányai 1 m³-re vonatkoztatva

Fiber type	Length (mm)	Diameter (mm)	Density (kg/m ³)	Tensile strength (MPa)
Hooked-end	35 ±5%	0.6 ±5%	7 850	1350

Table 2 Technical properties of the steel fibers
2. táblázat Az acélszálak műszaki jellemzői

A fiber volume content of 6% was selected in this study for the hooked-end fiber, as it was the most appropriate for the dimensions of the molds utilized. The mixing method adopted for the SIFCON mixture was developed based on previous studies and preliminary trials to ensure optimal workability. The mixing process involved initially blending the dry components for 3 minutes. Subsequently, two-thirds of the water, pre-mixed with the superplasticizer, was added and mixed for another 3 minutes. The remaining one-third of the water, also containing superplasticizer, was then introduced, and mixing continued for an additional 2 minutes.

2.2 Casting and testing samples and specimens

This investigation involved testing the compressive and flexural strengths of both NSC and SIFCON materials. Compressive strength was evaluated using cubes with dimensions of 150 mm for NSC and 100 mm for SIFCON. Flexural strength was assessed through prism specimens, sized 70×70×250 mm for NSC and 40×40×160 mm for SIFCON. For each test type and material, the reported values represent the results for 7 and 28 days.

The main objective of this study is to examine the structural behavior of flat slabs when using SIFCON in full or in part. The type of fibers used in SIFCON is hooked-end steel fiber. The experimental program consisted of testing 5 slab specimens; one reference specimen was cast with NSC. 2 NSC-SIFCON hybrid flat slab specimens with flexural reinforcement cast by using SIFCON partially over an extended area in a form similar to a cross-shaped shear reinforcement and full or partial depth. 2 SIFCON flat slab specimens cast by using SIFCON entirely with or without flexural reinforcement. In this study, square concrete slabs were utilized as test specimens, each measuring 600 mm on each side with a constant thickness of 60 mm. The specimens were classified according to the SIFCON concrete, the type of fibers used, or the depth of the SIFCON in composite slabs, as presented in Table 3. Fig. 3 shows the overall slab geometries and reinforcement layout details.

Symbol	Details
N	Normal strength concrete (NSC) flat slab
S	Slurry infiltrated fiber concrete (SIFCON) flat slab without flexural reinforcement
S+R	Slurry infiltrated fiber concrete (SIFCON) flat slab with flexural reinforcement
N-S2+	NSC flat slab – the SIFCON in a cross-shaped form with 20 mm depth in the tension side
N-S6+	NSC flat slab – the SIFCON in a cross-shaped form with full flat slab depth

Table 3 The symbols of the slab and their meanings.
3. táblázat A födécek jelölései és jelentésük

Prior to the casting process, all constituent materials were carefully prepared and proportioned according to the mix volume. The flat slab specimens, each measuring 600×600×60 mm, were formed using wooden molds supported by external iron frames and placed on a steel base to ensure dimensional stability throughout the casting. Before each casting, molds were thoroughly cleaned, coated with release agent, and leveled on a flat surface.

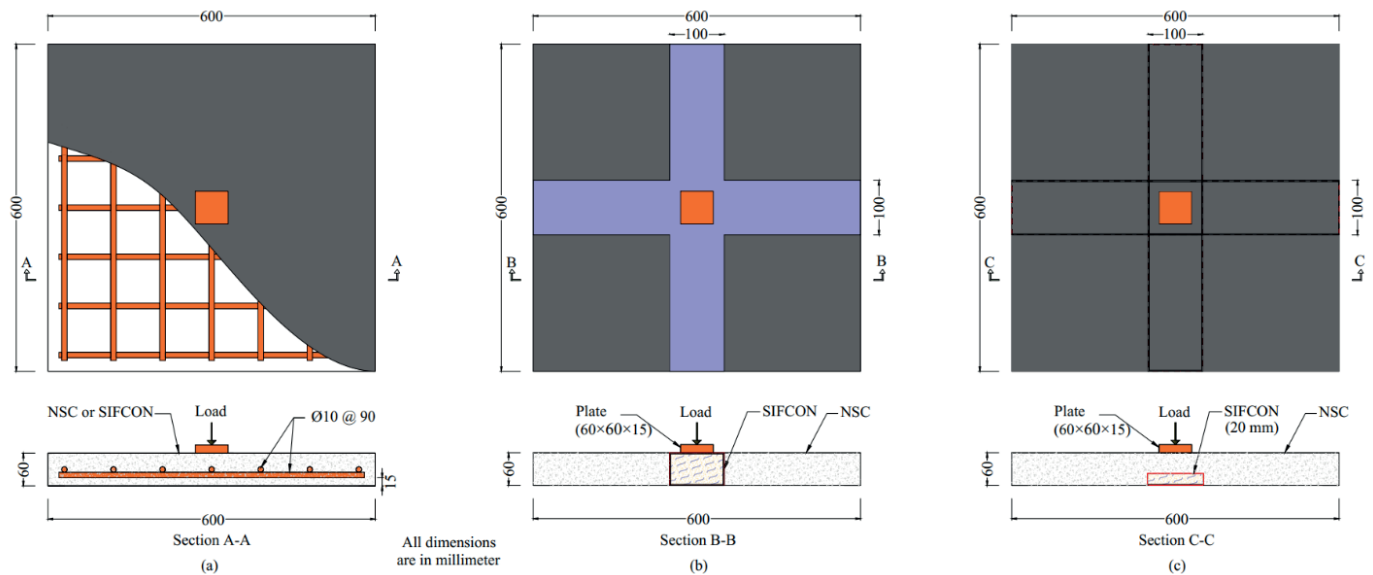


Fig. 3 Specimen dimensions and layout: (a) NSC or SIFCON flat slab with reinforcement details; (b) Hybrid flat slab with full depth of SIFCON; (c) Hybrid flat slab with partial depth of SIFCON

3. ábra A próbatetek méretei és elrendezése: (a) NSC vagy SIFCON síkfödém vasalási részletekkel; (b) Hibrid síkfödém teljes vastagságú SIFCON réteggel; (c) Hibrid síkfödém részleges vastagságú SIFCON réteggel

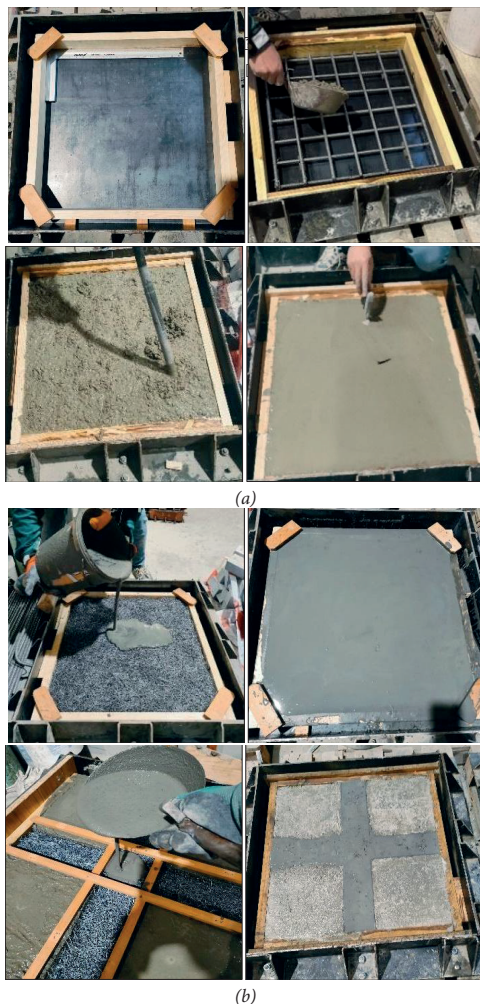


Fig. 4 The steps of casting the different types of flat slab concrete (a- NSC flat slab, b- SIFCON slab and NSC-SIFCON flat slabs).

4. ábra A különböző típusú síkfödém betonok betonozási lépései (a- NSC síkfödém, b- SIFCON födém és NSC-SIFCON síkfödémek)

The sequence of casting for various concrete types is illustrated in Fig. 4. For slabs made with NSC, reinforcement meshes were accurately placed inside the molds, ensuring proper bottom cover. In SIFCON slabs, the steel fibers were introduced in a single batch into the mold before the slurry was poured, allowing the mix to penetrate and encapsulate the fibers.

In the case of hybrid flat slabs, a fine galvanized steel mesh was positioned precisely at the interface between the NSC and SIFCON regions. This mesh was anchored to the bottom reinforcement and held in position from above using a wooden formwork system to control the geometry, as shown in Fig. 5b.

Upon completion of the 28-day curing period, structural load tests were performed on all slab specimens under monotonically increasing central loading until ultimate failure was reached. The loading way utilized a precision-calibrated electro-hydraulic testing machine with a rated capacity of 600 kN, as depicted in Fig. 5. The load application was controlled to ensure uniform rate progression and avoid dynamic effects. Each slab was simply supported along all four sides over an effective span of 500 mm using a custom-fabricated steel frame integrated within the testing setup. Loading was applied using a 60×60 mm steel stub column. All tests were conducted under a controlled displacement rate of 0.5 mm/min. To monitor deflection behavior, linear variable differential transducers (LVDTs) were positioned at the slab center and two quarter-span points on opposite sides of the applied load. Key response parameters recorded included the cracking load, the ultimate load associated with punching shear or flexural failure, mid-span deflection, and the averaged deflections at the quarter-span points.

The ultimate deflection was defined following Kaka et al. [16] as the deflection corresponding to a post-peak load reduction to 80% of the maximum load. Given the emphasis on the high ductility behavior of SIFCON in this investigation, particular attention was directed to the structural response beyond the peak load. Two critical deflection points in the post-peak stages were identified: one at 80% and the second at 60% of the peak load. These deflection values are referred to herein as u_1 and u_2 , respectively, and were used to assess the residual

load-carrying capacity and the contribution of fibers under advanced deformation.

3. Results and discussion

3.1 Mechanical properties

In this work, the flexural and compressive strengths of SIFCON and NSC concrete are tested. The cubes and prisms made for this purpose were evaluated for compressive and flexural strength at 7 and 28 days. The NSC and SIFCON are displayed in Table 4. The findings demonstrate that SIFCON with hooked-end steel fiber has a substantially higher compressive and flexural tensile strength than NSC. The capacity of fibers to limit and stop fracture development, as well as to reduce the rate and direction of crack propagation, can be explained by their increased strength. Table 4 also shows the increases in both compressive and flexural strength for SIFCON relative to the reference NSC at 28 days.

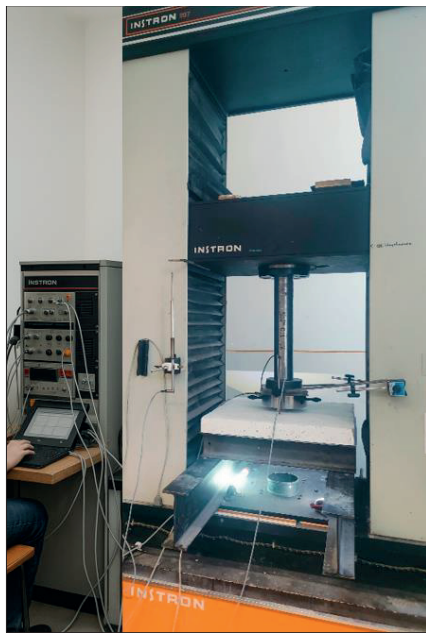


Fig. 5 Punching shear test of flat slabs
5. ábra Síkfödémek átszúródási nyíróvizsgálata

Type of concrete	Compressive strength (MPa)		The standard deviation	Flexural strength (MPa)		The standard deviation	The percentage increase (%) in 28 days compared to NSC	
	7 days	28 days		7 days	28 days		Compressive strength	Flexural strength
NSC	31	43	1.4	3.7	4.8	0.4	–	–
SIFCON	89	118	3.08	23.5	32	2.2	174	567

Table 4 The mechanical properties results of the NSC and SIFCON
4. táblázat Az NSC és a SIFCON mechanikai tulajdonságainak eredményei

3.2 First crack strength

The first crack loads, for the various slabs, are summarized in Table 5. Also, the same table shows the deflection of the center and the average deflection of two quarters at the first crack. The results show that using SIFCON increased the first crack

strength of the slab. The first crack strength increased for hybrid slabs by 56% for the slab in which the SIFCON was used in the form of a cross-shaped with full depth. The highest percentage increase in first crack was reached in the slab made entirely of SIFCON using hooked-end steel fibers. The percentage in the S+R slab reached 342%.

The main reason behind SIFCON's remarkable ability to withstand first cracking loads is its dense fiber, which comprises 6% of the slab's volume. The closely spaced steel fibers intersect at every potential crack plane, so once a microscopic crack forms, the fibers bridge it, absorbing tensile forces and distributing stress over a much larger area. This bonding keeps crack widths microscopic, meaning the element must be subjected to significantly greater external loads before any visible cracking becomes apparent.

Specimen	P_{cr} (kN)	Δ_c (mm)	Δ_q (mm)	η_f (%)
N	11.18	1.23	0.21	–
S	42.72	2.61	2.35	282
S+R	49.43	2.95	2.69	342
N-S2+	16.92	1.83	1.20	51
N-S6+	17.43	1.91	1.24	56

Note: P_{cr} = First cracking load; η_f = The percentage of improved first crack strength compared to specimen N; Δ_c = Center deflection at first cracking load; Δ_q = Quarters av. deflection at first cracking load.

Table 5 The first crack load and deflection of the specimens at the first cracks
5. táblázat Az első repedéshez tartozó teher és lehajlás a próbatesteknél

3.3 Failure mode and crack pattern

Fig. 6 maps the cracking patterns that developed on the tension face of every slab. Three discrete failure mechanisms were identified: punching shear, flexure, and a coupled punching shear-flexural mode. The reference specimen N failed in punching shear: radial cracks nucleated directly beneath the load and spread outward to form a circumferential ring, accompanied by local concrete spalling. A purely flexural response characterized S and N-S2+ specimens, where cracks originated at mid-span and propagated diagonally toward the supports. Specimens S+R and N-S6+ exhibited the mixed mode: load-induced longitudinal cracks first appeared parallel to the reinforcement, then evolved into diagonal and peripheral circular cracks. In hybrid slabs, the initial crack consistently formed along the interface between the SIFCON layer and the surrounding NSC, and continued outward until the peak load, when the punching shear cone was fully established.

Deflection records underscore the ductility advantages conferred by SIFCON. The reference N slab displayed virtually no post-peak deformation, 4.82 mm at peak load and 5.33 mm at the u_2 stage, revealing a brittle response. In contrast, SIFCON and hybrid flat slabs showed substantial displacement capacity beyond first cracking. The most pronounced increase occurred in the S+R specimen, whose deflection rose from 12.6 mm at peak load to 24.8 mm at u_2 . This post-peak ductility grew with the SIFCON volume fraction. Moreover, hooked-end steel fibers improved energy absorption and postponed failure, reaffirming that a higher fiber dosage markedly enhances both ductility and load-carrying capacity in the later stages of loading.

3.4 Peak load and load-deflection response

Table 6 compiles the maximum (peak) loads, the corresponding mid-span deflections, and the average deflection of two quarters at the peak load, together with the percentage increase in peak load relative to the reference slab N. Fig. 7 charts the complete load-deflection curve for each specimen. The data confirm that enlarging the SIFCON portion of a slab generally raises its punching shear capacity.

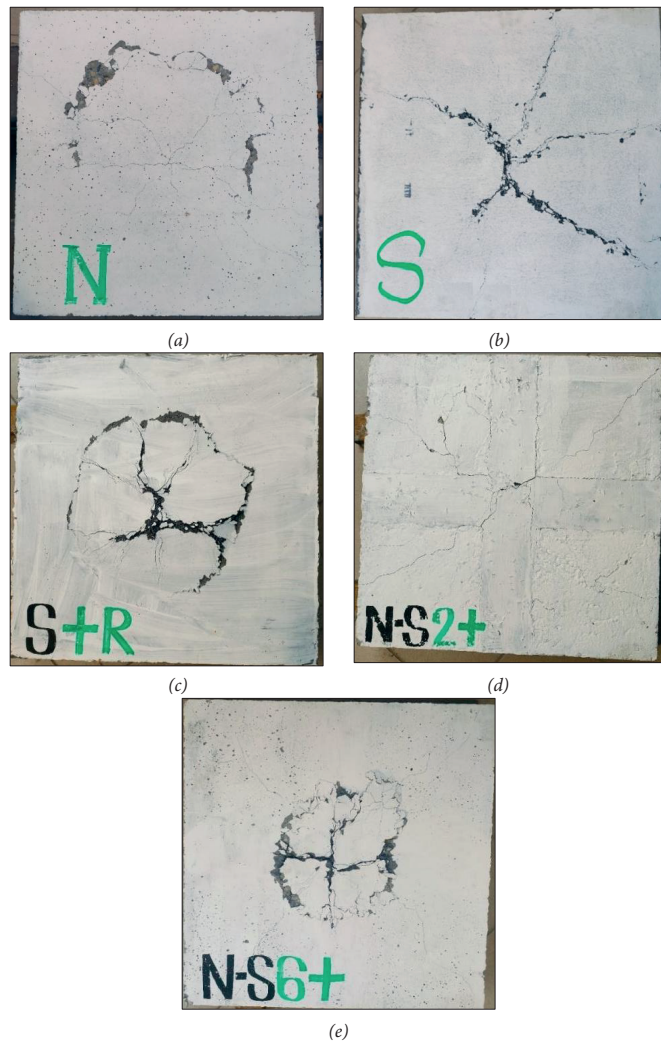


Fig. 6 Crack pattern on the tension face of flat slab specimens:
(a) N; (b) S; (c) S+R; (d) N-S2+; (e) N-S6+
6. ábra Repedéskép a síkfödém próbatetek húzott oldalán:
(a) N; (b) S; (c) S+R; (d) N-S2+; (e) N-S6+

The greatest strength enhancements were obtained for slab S+R, whose peak loads were 118% higher than those of the N flat slab. Among the hybrid cross-shaped specimens, the best performance was achieved by N-S6+ flat slab, which exceeded the reference slab's peak load by roughly 36%. Also, the presence of SIFCON altered the failure mode from brittle to a more ductile flexural response. For hybrid slabs, the gap between u_1 and u_2 widened as the thickness of the SIFCON layer was increased. In slabs cast entirely with SIFCON, this deflection gap was larger in the S+R slab, further promoting a switch from punching to flexural failure and greatly enhancing ductility, as observed in S and S+R specimens.

Overall, the study demonstrates that even a modest amount of SIFCON, applied as a cross-shaped throughout the thickness, can deliver substantial strength gains while providing excellent ductility. The difference between the deflection at peak load and the u_2 stage reached roughly 12 mm in N-S6+ slab cases. These findings emphasize the promise of SIFCON for flat slab construction: significant improvements in capacity and toughness can be achieved without increasing slab thickness, adding drop panels, or column capitals.

Specimen	P_p (kN)	Δ_{cp} (mm)	Δ_{qp} (mm)	η_p (%)
N	50.18	4.82	2.25	–
S	93.14	7.74	4.25	86
S+R	109.3	5.25	8.41	118
N-S2+	56.01	8.41	3.21	12
N-S6+	68.05	11.46	3.32	36

Note: P_p = Peak load by (kN); Δ_{cp} and Δ_{qp} = Center and Quarters av. deflection by (mm) at peak load, respectively; η_p = The percentage of improved peak load compared to specimen N.

Table 6 The peak load and deflection of the specimens at the peak load
6. táblázat A maximális teher és a hozzá tartozó lehajlás a próbateteknél

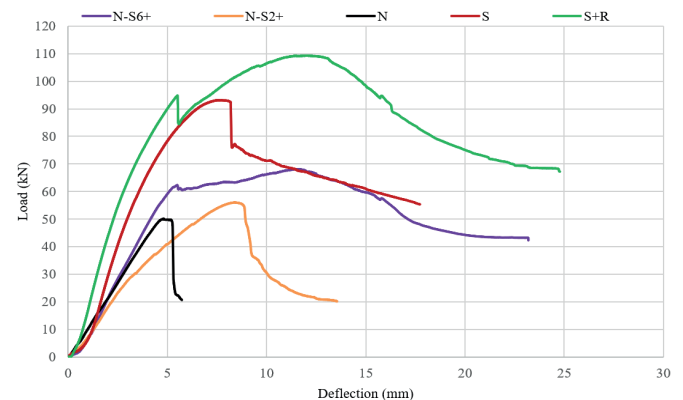


Fig. 7 The load-center deflection curves of all specimens
7. ábra Az összes próbatest teher-középponti lehajlás görbéje

3.5 Ductility

Ductility, μ , describes the capacity of a structural member to undergo substantial deformation after yield. In this study, it is expressed as the ratio of the ultimate displacement, Δ_u , to the corresponding yield displacement, Δ_y , by Eq. (1) and the procedure proposed by Lim and Hong [17]. The ultimate displacement is taken as the deflection recorded when the applied load has fallen to 80% of the specimen's peak value. The secant stiffness at a point two-thirds of the measured peak load is used to idealize the elastoplastic curve that passes through the peak point of the load-deflection curve, and the displacement at an intersecting point between the two lines is used to determine the yield point on the curve [17-19].

Because the slabs exhibited continuing deformation after peak load, ductility ratios were evaluated at two ultimate stages, u_1 and u_2 , to capture the influence of fiber reinforcement on post-peak behavior. The resulting indices, μ_1 and μ_2 , are reported in Table 7 and provide a clearer picture of how fiber type and distribution affect the later stages of the response.

$$\mu = \frac{\Delta_u}{\Delta_y} \quad \text{eq. (1)}$$

Specimen	P_y (kN)	Δ_{cy} (mm)	Δ_{cu1} (mm)	Δ_{cu2} (mm)	μ_1	μ_2	$\eta_{\mu 1}$ (%)	$\eta_{\mu 2}$ (%)
N	48.90	4.65	5.22	5.30	1.12	1.14	–	–
S	83.44	5.56	8.85	17.54	1.59	3.15	42	176
S+R	93.94	5.40	16.71	24.78	3.09	4.59	176	303
N-S2+	49.99	6.67	9.1	9.72	1.36	1.46	21	28
N-S6+	61.00	5.68	16.36	23.51	2.88	4.14	157	263

Note: P_y = yield load by (kN); Δ_{cy} = Center deflection by (mm) at yield load;
 Δ_{cu1} and Δ_{cu2} = Center ultimate deflection by (mm) u_1 and u_2 respectively;
 μ_1 and μ_2 = the ductility 1 and 2; $\eta_{\mu 1}$ and $\eta_{\mu 2}$ = The percentage of improved ductility 1 and 2 compared to specimen N.

Table 7 The ductility results
 7. táblázat Duktilitási eredmények

Table 7 demonstrates that embedding SIFCON in the slab markedly elevates its ductility. During the stage u_1 , ductility increases steadily, while a far more pronounced gain emerges in the second stage u_2 . For hybrid flat slabs, most clearly in specimen N-S6+, where a cross-shaped SIFCON extends through the full thickness, the greatest benefit appears in the transition between these two stages. After the longitudinal reinforcement fully yields, the SIFCON fibers engage, bridging and confining cracks so effectively that the slab sustains its load-bearing capacity for an extended period, and the failure mode shifts from brittle to ductile. These results confirm the study's key premise: outstanding ductility can be achieved with only a modest volume of SIFCON.

3.6 Inclination of cracks and rotation of slabs

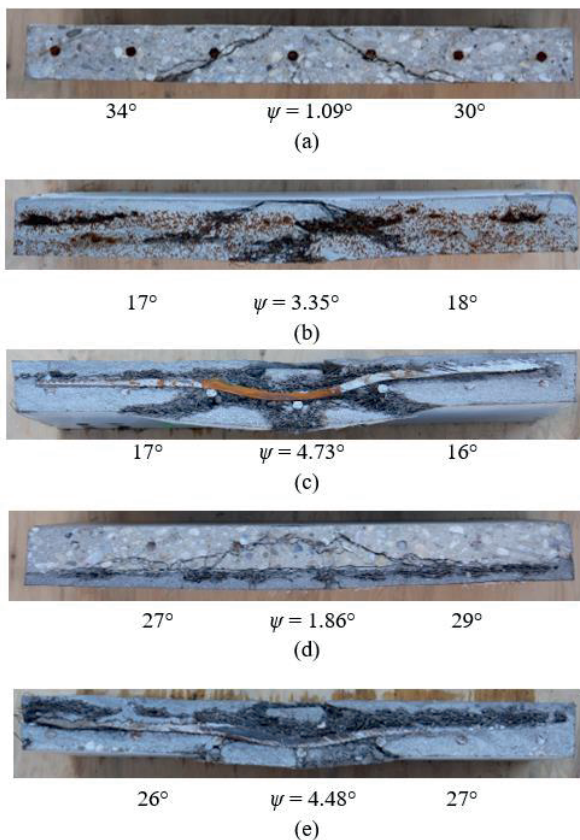


Fig. 8 Inclination of cracks and rotation of flat slab specimens: (a) N; (b) S; (c) S+R; (d) N-S2+; (e) N-S6+

8. ábra A repedések dőlésszöge és a síkfödém próbatestek elfordulása: (a) N; (b) S; (c) S+R; (d) N-S2+; (e) N-S6+

After completing the slab tests, the rotation of each slab about the loading zone was recorded, and the specimens were subsequently sectioned longitudinally to delineate the dominant crack patterns Fig. 8. By mapping cracks on both the top and bottom faces, the punching shear cone angle, defined as the inclination between the failure surface and the vertical plane, was established. Results show that this angle on the tensile face decreases monotonically with higher SIFCON content. This finding demonstrates that the critical cracks migrate progressively away from the critical punching shear area, transforming the failure mode from brittle to ductile. Moreover, the slab's rotation angle increases with SIFCON incorporation, particularly when larger SIFCON regions are provided.

4. Conclusion

This study evaluates the structural performance of flat slabs strengthened either fully with SIFCON or partially through a hybrid system combining SIFCON with NSC. The experimental program measured the compressive and flexural strengths of both SIFCON and NSC, determined punching shear load, deflection, ductility, and rotation, and recorded crack patterns together with crack inclinations. The results highlight the efficiency of adding SIFCON in boosting punching shear capacity and improving the behavior of flat slabs. The study presents a series of conclusions:

1. At 28 days, SIFCON had greater compressive and flexural strengths of 118 and 32 MPa, respectively. Comparing SIFCON to the reference NSC, the percentage increase in compressive and flexural strength of SIFCON was 174% and 567% respectively.
2. The slabs made entirely of SIFCON demonstrated a substantial improvement in the first cracking load. With a 342% improvement above the reference N flat slab, and in hybrid flat slabs, the increase in first cracking load was 56%.
3. When compared to the N flat slab, the maximum load capacity of the SIFCON flat slab shows a significant improvement. The higher percentage increase for SIFCON flat slabs compared to the reference N flat slab was 118% for the S+R specimen, and for the hybrid flat slabs, it was 36% for the N-S6+ specimen.
4. The load-deflection curves showed that all the slabs that used SIFCON entirely or partially had a high ductility and gradual post-peak decline, unlike the N flat slab, which failed suddenly. The percentage increase in ductility $\eta_{\mu 2}$ was 303% in the S+R slab and 263% in the N-S6+ slab at the u_2 stage compared to the reference N flat slab.
5. The average inclination angle of the punching shear cone cracks of the N flat slab is about 32°. On the other hand, the SIFCON slabs record 17°, demonstrating the material's exceptional capacity to prevent cracks. The smallest angle of the hybrid flat slabs was 26° for the N-S6+ specimen. The rotation of the S+R flat slab around the load point reaches roughly 4.7°.

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