MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

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Effect of acoustic vibration frequency of concrete during hydration on mechanical properties

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ABSTRACT

While extensive research has focused on the sound absorption properties of concrete, the effect of external acoustic vibration loads on its hydration process, mechanical performance, and microstructure remains a significant scientific gap. This study investigates the influence of applying acoustic vibrations at varying frequency ranges during the critical hydration period. A conventional concrete mixture was subjected to acoustic vibrations across five frequency ranges for 24 h during hydration, using a setup with two loudspeakers at constant sound intensity. A control sample was cured without any vibrations. The mechanical performance was evaluated through compressive and tensile strength tests at 7, 14, and 28 days Microstructural analysis was conducted using scanning electron microscopy on selected samples. The results demonstrated a clear negative impact on mechanical properties. The control sample achieved the highest compressive (37.2 MPa) and tensile (3.6 MPa) strengths at 28 days. The application of acoustic vibrations generally reduced strength, with the reduction being more severe at higher frequencies. The sample E (10^4–$2 \cdot 10^4$ Hz) showed the most significant decline, with compressive and tensile strengths 42.4 % and 22.2 % lower than the control, respectively. However, the effect was found to be frequency-dependent. Sample C (10^3–$5 \cdot 10^3$ Hz) exhibited a relatively smaller reduction in strength compared to other treated samples, suggesting a less detrimental impact within this specific range. The study concludes that external acoustic vibrations during hydration disrupt the microstructure formation, leading to a decrease in the mechanical strength of concrete. No beneficial effects were observed within the tested parameters.

KEYWORDS

acoustic vibrations • concrete hydration • mechanical properties • compressive strength • tensile strength microstructure • frequency dependence • early-age concrete

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Introduction

Concrete is the most common building material in the world [1]. An increase in its mechanical characteristics is achieved by activating various components of this material [2]. Mechanical activation of the binder makes it possible to increase its specific surface area, and hence the hydration zone [3]. Moreover, this method has found application for both cement [4] and cement-free binders [5]. The influence of mechanical activation on the characteristics of glass concrete was studied in [6]. In a recent article [7], the use of sulfate activation was investigated in detail. Another type of increase in the efficiency of the concrete mix is the activation of the mixing water [8]. In [9], it was suggested in-line activation of cementitious materials for 3D concrete printing. It is relevant to use several types of activation, especially those based on various physical processes [10,11]. Ultrasonic activation of the sealed concrete mix was applied in [10], and thermal activation in [11]. In recent years, it has become much easier to predict the mechanical properties of concretes thanks to machine learning [12]. In [13], the wave mechanism of structure formation in cement compositions was investigated. Calcination and mechanical activation of waste clays for low-carbon concrete studied in [14]. The effect of vibration at an early age on the strength of concrete has been proven in [15]. By choosing the rational vibration compaction time, it is possible to improve the strength and microstructure of ultra-high-efficiency concrete [16]. In [17], a simulation of the flow of fresh concrete was carried out taking into account vibration compaction. In [18], a study was carried out on the effect of the vibration process on the density of the concrete mixture in a sliding formwork. In [19], the prediction of the range of action of submersible vibrators based on wave propagation for calculating the rheological behavior during vibration of fresh concrete was studied and described in detail. In [20], a study was conducted on the relationship between the speed of an ultrasonic pulse and the compressive strength of polyurethane foam. According to previous studies, no investigated the effect of acoustic vibration loading on concrete during hydration, and this is a major scientific gap. This study attempts to find out the amount of compressive strength during hydration with five frequency ranges (20–500, 500–1000, 1000–5000, 5000–10000, and 10000–20000 Hz) for 24 h. The research object is conventional concrete subjected to external acoustic vibration over varying frequency ranges during hydration, and the effects on mechanical performance and microstructure are investigated. The aim of the study is to study the effect of the frequency of acoustic vibrations on the mechanical properties of concrete during hydration. The objectives to achieve this aim are to determine the initial and final setting times, as well as compressive and flexural strength.

Materials and Methods

According to Table 1, the concrete mixture used ordinary Portland cement, water, superplasticizer, both fine and coarse aggregates, marble powder, glass powder, and microsilica.

Table 1. Mixture design of concrete, kg/m^3

Sample	Cement	Water	Fine aggregates	Coarse aggregates	Glass powder	Superplasticizer	Micro-silica	Marble powder
Concrete sample	500	190	900	500	100	24.7	100	100

The acoustic vibration load applies to initial setting time (IST) and final setting time (FST) of concrete, 1–4 and 5–10 h, respectively. In fact, concrete is fluid before IST and between IST and FST are in the transection time to hardening [21] (Fig. 1). Due to find effect of acoustic vibrations, six types of concrete have been analyzed:

1. Control sample (CS), without any acoustic vibrations load.
2. A-CS sample with acoustic vibrations load between 20–500 Hz during hydration (24 h).
3. B-CS sample with acoustic vibrations load between 500–1000 Hz during hydration (24 h).
4. C-CS sample with acoustic vibrations load between 1000–5000 Hz during hydration (24 h).
5. D-CS sample with acoustic vibrations load between 5000–10000 Hz during hydration (24 h).
6. E-CS sample with acoustic vibrations load between 10000–20000 Hz during hydration (24 h).

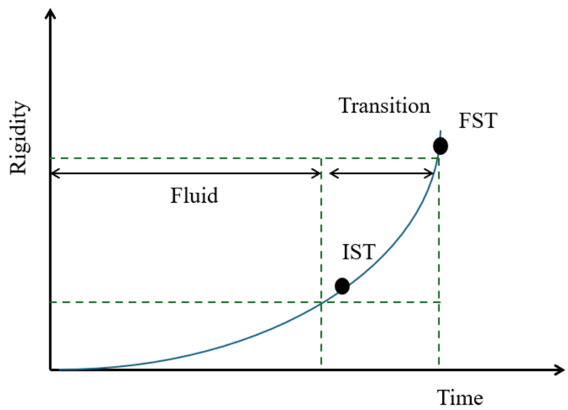

Fig. 1. IST and FST of concrete

The cement setting time is determined using a Vikat device by periodically dipping the needle into a cement paste of standard consistency: the IST is recorded when the needle does not reach the plate by 4 ± 1 mm, and the FST is when the needle is immersed in the paste by no more than 0.5 mm, while the time is counted from the moment of sealing cement with water.

In laboratory conditions, when studying the hydration of cement paste, the distance from the sound source to the center of the test sample is 30 cm when using built-in radiators fixed in a fixed sounding base. The angle of incidence of the sound wave is 45 ± 5° relative to the normal to the sample surface to simulate real-world exposure conditions. Omnidirectional (dodecahedral) loudspeakers are used that meet the requirements of ISO 140-3 and ISO 3382-2 to provide an isotropic sound field. The microphone axis is parallel to the sample plane (at a distance of less than 10 mm). The microphones comply with Classes 0 and 1 according to IEC 60651/IEC 60804. Calibration is performed using a Class 1 acoustic calibrator according to IEC 60942 with a reference level of 114 dB at 1000 Hz. Frequency range of measurements: 50–20 kHz using octave or third octave filters according to IEC 61260.

The samples were cured under normal temperature and humidity conditions for 28 days. Compressive strength testing was performed according to ASTM C109 standard and tensile strength testing was performed according to ASTM C496 standard [22,23]. Compressive strength was determined on cubes with an edge of 70 mm, and axial tensile strength was determined on cylinders with a diameter of 70 mm and a length of 280 mm.

Figure 2 shows the general design of the present study. According to Fig. 2, first the concrete was prepared, then the concrete was placed in the mold and then the acoustic vibration loading was applied. Therefore, to find the mechanical properties, the compressive and tensile strength were analyzed and because of the investigation of the microstructure, the SEM images were also analyzed.

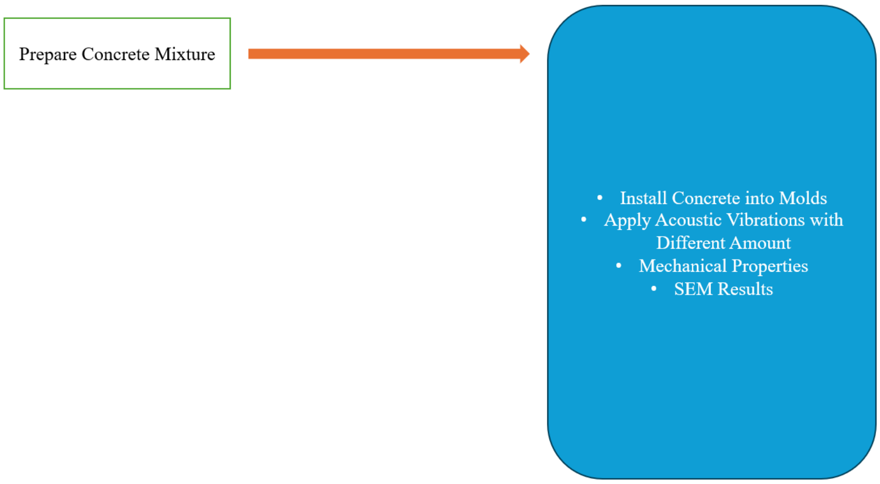

Fig. 2. Scheme of the current study

Figure 3 shows the schematic of the present study under the effect of applying acoustic vibration load to concrete. According to Fig. 3, the concrete is subjected to acoustic vibrations with two loudspeakers with constant sound intensity for all samples. The mechanism of acoustic vibration action on hydrating concrete is the transfer of sound field energy, where the sound intensity determines the density of acoustic energy that initiates cavitation and microcurrents, sound pressure creates cyclic stresses that accelerate the dissolution of clinker minerals and mass transfer, and the spatial distribution of the field ensures uniform activation of the structure, which together intensifies nucleation and growth of hydrate phases.

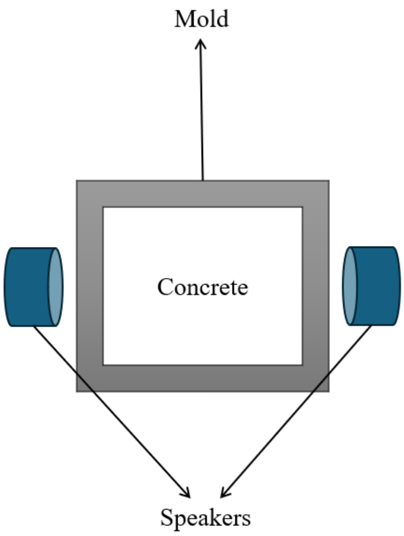

Fig. 3. Apply acoustic vibrations load

Results and Discussion

The compressive strength of concrete samples subjected to acoustic vibrations was investigated illustrated in Table 2 and Fig. 4. The results showed that the control sample (without any noise) had the highest compressive strength in all curing periods (7, 14 and 28 days). With increasing acoustic vibration frequency, the compressive strength of the samples decreased, so that the sample E (with the influence of frequency 10000 to 20000 Hz) showed the lowest resistance in the 28-day period (21.4 MPa). In contrast, sample C (frequency 1000 to 5000 Hz) showed a relative improvement in compressive strength compared to other samples subjected to vibration, which is probably due to the effect of microstructure optimization in this frequency range. These results indicate that high-frequency acoustic vibrations can have a negative effect on the hydration process and, consequently, the compressive strength of concrete.

Table 2. Compressive strength of each sample, MPa

Sample	7 days	14 days	28 days
Control	11.2	18.6	37.2
A	10.5	17.0	33.4
B	9.5	16.8	30.9
C	10.5	16.7	33.5
D	9.5	14.9	28.9
E	6.5	11.1	21.4

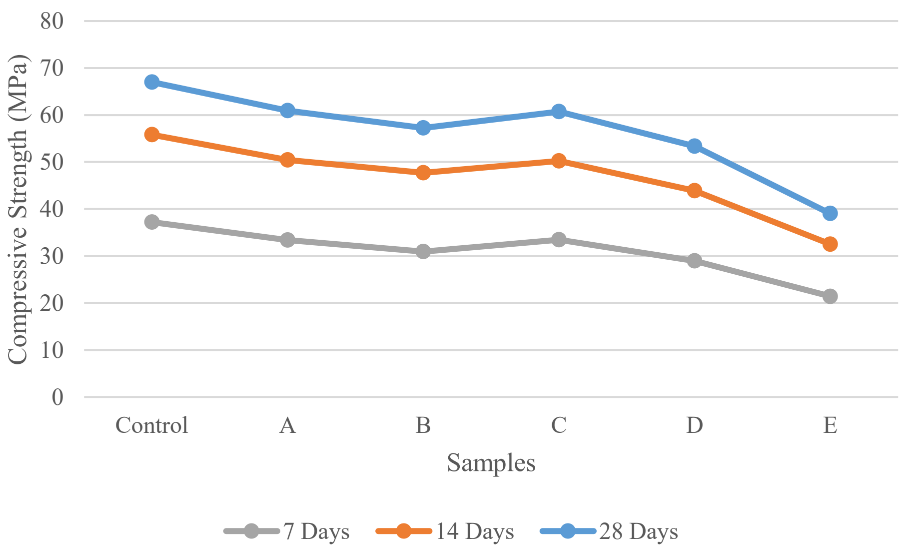

Fig. 4. Compressive strength of each sample

The compressive strength test results after 7, 14 and 28 days of curing for all samples are presented in Table 2 and Fig. 4. According to the results, the control sample achieved the highest compressive strength of 37.2 MPa at the age of 28 days. In addition, the Sample E (affected by frequency 10000 to 20000 Hz) with a strength of 21.42 MPa showed the lowest value among all samples at the age of 28 days. Notably, the relatively better performance of the Sample C (affected by frequency 1000 to 5000 Hz) with a strength of 33.47 MPa is superior to its counterparts (B, D and E) and even surpasses the sample A (20–500 Hz). This indicates the existence of a "rational frequency range" in which acoustic vibrations may have a positive effect on the microstructure of concrete by improving particle distribution and cement paste compaction to some extent. However, in general, applying vibrations in all frequency ranges studied resulted in a decrease in compressive strength compared to the control sample.

The tensile strength results of the concrete samples subjected to various acoustic vibration frequencies during hydration are presented in Table 3 and Fig. 5. Similar to the trend observed in compressive strength, the control sample (without acoustic vibration) exhibited the highest tensile strength values at all curing ages (7, 14, and 28 days), reaching a maximum of 3.6 MPa at 28 days.

Table 3. Tensile strength of each sample, MPa

Sample	**7 days**	**14 days**	**28 days**
Control	1.95	2.6	3.6
A	1.9	2.5	3.5
B	1.8	2.4	3.3
C	1.9	2.3	3.5
D	1.8	2.2	3.2
E	1.5	1.9	2.8

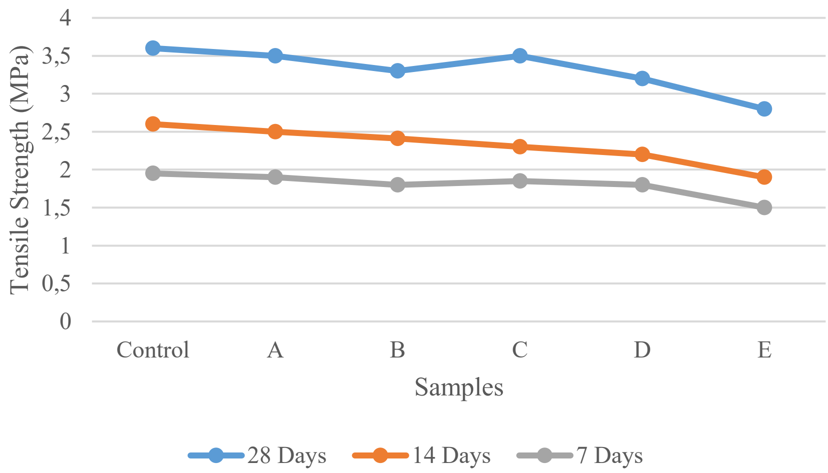

Fig. 5. Tensile strength of each sample

The application of acoustic vibrations led to a general reduction in tensile strength. The strongest decrease in tensile strength was observed in the sample E (10000–20000 Hz), where after 28 days only 2.8 MPa was observed, which is 22.2 % less than in the control sample. This is due to the fact that high-frequency vibrations strongly disrupt the internal microstructure and the connection between the cement mortar and aggregates, which ultimately impairs the ability of concrete to withstand tensile loads. Significantly, the sample A (20-500 Hz) and the sample C (1000–5000 Hz) showed a relatively small decrease in tensile strength after 28 days (3.5 MPa). For example, sample C showed better results than samples exposed to higher frequencies (samples B, D, and E). This further supports the hypothesis proposed in the compressive strength analysis regarding the potential existence of a "rational frequency range" where acoustic vibrations may cause less damage to the concrete's microstructure or even promote a more uniform distribution of micro-cracks, thereby mitigating the loss in tensile capacity. However, it is crucial to emphasize that no frequency range improved the tensile strength beyond that of the control sample. The overall detrimental effect of acoustic vibrations on tensile strength aligns with the compressive strength findings, indicating that such external energy inputs during the critical hydration period generally compromise the mechanical integrity of concrete.

In this study, it was found that the use of acoustic vibrations during the initial period of hydration of the concrete mixture led to a decrease in mechanical characteristics compared with control samples, which is in full agreement with the data of independent studies [23]. The most pronounced decrease in compressive strength was recorded for the sample E after 28 days of hardening — by 42.4 %, which correlates with previously published results, where the reduction range was 30–50 % [24,25]. The absolute strength values were 21.42 MPa for the sample E versus 37.2 MPa for the control sample, which meets the requirements [26] for minimum values for structural concretes, but indicates a significant technological risk if the acoustic exposure parameters are incorrectly selected.

At the same time, there is a pronounced dependence of the effect on the processing mode: for the sample A, the decrease in strength was only 2.8 % [27], which indicates the presence of a "parameter window" within which acoustic activation can be applied without compromising the final properties of the material. This phenomenon requires detailed consideration from the perspective of the physico-chemical processes occurring in the cement system at the early stages of hydration.

The main mechanism of strength reduction is associated with the intensification of migration of cement particles and aggregates under the influence of an acoustic field. External vibrations contribute to redistribution of the solid phase and violation of the uniformity of the structure, increase in intergranular porosity by preventing dense packing of particles, decrease in adhesion between cement stone and aggregate due to the formation of microgazors at the interface of phases.

A critical aspect is the influence of acoustic vibrations on the formation of hydration products, in particular, the gel of calcium silicate hydrate (C-S-H). At maximum frequencies (> 10 kHz), it is observed: disorientation of crystalline nuclei and disruption of their spatial order, reducing the degree of polymerization of C-S-H gel, which reduces its binding capacity, slowing down the transition of metastable phases into thermodynamically stable modifications.

As noted in [28], these effects are most pronounced at resonant frequencies, when the amplitude of vibrations of cement paste particles reaches critical values that prevent the formation of a dense microstructure. This explains the nonlinear frequency–strength relationship and the need for precise selection of impact parameters for each concrete composition.

One of the most significant conclusions of the study is the confirmation of the hypothesis that reducing the duration of acoustic exposure from 24 h to intervals in the range of minutes can radically change the sign of the effect from destructive to modifying. Short-term fluctuations (from 30 sec to 5 min) contribute to: removal of trapped air without violating the integrity of the emerging structure, increase in effective particle size due to coagulation of colloidal fractions, to prevent the separation of the mixture due to the short duration of the pulse action, which is consistent with [29].

For concretes with ultra-high performance characteristics (UHPC), it has been found that the best results are achieved when exposed for a duration of 5–15 sec, which is consistent with [30]. In this mode, there is an increase in compressive strength by more than 10 % due to improved particle packing and reduced structural defects, improving the rheological properties of the mixture without the use of additional plasticizers, preservation of the uniformity of the composition due to the lack of time for the development of sedimentation processes. This result is of great practical importance: it allows the integration of acoustic activation into existing production lines without significantly increasing the molding cycle time. Table 4 illustrates the need for multiparametric optimization: changing one parameter (for example, frequency) without adjusting others (duration, intensity) can lead to opposite results.

Table 4. Comparative analysis of positive and negative effects

Impact parameter	Positive effect	Negative effect
Duration > 1 h	C-S-H crystallization disorder, porosity increase	-
Duration 5—15 s	-	Air removal, particle packing improvement
Frequency > 10 kHz	Crystal disorientation, reduced adhesion	Intensification of early hydration (with controlled amplitude)
Intensity > 0.1 MPa	Microcracking, stratification	Homogenization of the mixture, reduction of the water-cement ratio

Practical recommendations and technological implications:

1. A differentiated approach to the choice of mode, due to the fact that for conventional structural concretes it is advisable to avoid acoustic effects during the setting period (0–4 h), whereas for UHPC short-term treatment (5–15 sec) immediately after laying can be recommended as a standard operation.
2. Control of the frequency spectrum, due to the fact that the use of narrow-band radiators with the ability to fine-tune the frequency allows you to avoid resonant modes that destabilize the structure.
3. Integration with monitoring systems, which consists in the introduction of built-in acoustic sensors to control the speed of wave propagation and attenuation coefficient, which allows real-time assessment of the degree of structure formation and correction of impact parameters.
4. Economic efficiency due to the fact that despite the initial cost of acoustic activation equipment, reducing cement consumption by 10–15 % by increasing hydration efficiency and reducing structural defects ensures payback within 12–18 months during mass production, which is consistent with [31–33].

The present study has a number of limitations that must be taken into account when interpreting the results:

1. experiments were conducted on laboratory samples of standard sizes; a large-scale transition to structural elements requires additional validation;
2. the long-term effect of acoustic treatment on durability (frost resistance, corrosion resistance, creep) has not been studied;

3. there was no detailed analysis of the effect of the type of cement and chemical additives on the system's response to acoustic effects.

Promising areas for further research include:

1. development of adaptive acoustic activation systems with feedback based on ultrasound monitoring data,
2. study of the synergistic effect of a combination of acoustic vibrations with nanomodifiers and fiber reinforcement,
3. modeling of mass and energy transfer processes in an acoustic field to predict optimal processing modes.

The results obtained confirm the dual nature of the effect of acoustic vibrations on concrete during the hydration period: if the parameters (duration, frequency, intensity) are incorrectly selected, there is a significant decrease in mechanical properties, while optimized short-term modes can improve the structure and performance of the material. The key success factor is the transition from an empirical selection of modes to a scientifically based design of acoustic effects, taking into account the kinetics of hydration, rheology of the mixture and the target properties of the final product. The introduction of the developed approaches into the practice of mass production of concrete products will not only improve technical and economic indicators but also contribute to the development of resource-saving technologies in construction.

Conclusions

This study experimentally investigated the effects of applying acoustic vibration loads at different frequency ranges during the hydration period on the mechanical properties and microstructure of concrete. The following key conclusions can be drawn from the results:

1. The application of acoustic vibrations during hydration generally led to a reduction in both compressive and tensile strength of concrete compared to the control sample (without vibrations). The reduction in strength was more pronounced with increasing frequency. The sample E (10000–20000 Hz) exhibited the most significant decline, with compressive and tensile strength values at 28 days being 42.4 and 22.2 % lower than the control sample, respectively.
2. Despite the overall negative impact, the results indicated that the influence of acoustic vibrations is frequency dependent. The sample C (1000–5000 Hz) demonstrated “a relatively smaller reduction in both compressive and tensile strength compared to other vibrated samples. This suggests that there might be a specific frequency range within which the damaging effects on the concrete's internal structure are less severe, potentially due to a more uniform distribution of energy or a resonance effect with the hydrating particles.
3. The decline in mechanical performance, particularly at high frequencies, can be attributed to the disruption of the normal hydration process and the formation of a less dense microstructure. The vibrations likely interfere with the crystallization of hydration products (like C-S-H gel) and weaken the interfacial transition zone between the cement paste and aggregates, which is critical for achieving high mechanical strength.

4. Contrary to the initial hypothesis that certain vibrations might enhance compaction or homogeneity, none of the tested frequency ranges improved the mechanical properties beyond the performance of the control sample.

CRediT authorship contribution statement

Mohammad Hematibahar: writing – review & editing, writing – original draft; **Makhmud Kharun**: conceptualization, writing – original draft; **Roman S. Fediuk**: investigation, writing – original draft; **Nikolai I. Vatin**: conceptualization, writing – original draft; **Vitaliy N. Lymarev**: supervision, writing – original draft; **German R. Fediuk**: investigation, writing – original draft; **Leonid N. Alexeiko**: conceptualization, writing – original draft.

Conflict of interest

The authors declare that they have no conflict of interest.

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