Magnetizable Concrete Paves The Way For EV Charging And Low-Cost Power Magnetics

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MAGMENT magnetizable concrete materials—either cement- or asphalt-based—are a patented technology displaying the mechanical properties of conventional concretes due to the embedding of ferrite particles used as magnetic aggregates. These ferrite particles are obtained from recycled material from the ferrite industry and from the rapidly growing amount of electronic waste. It is worth noting that, unlike lithium, all chemical elements needed to produce this material (iron, manganese, zinc, calcium and aluminum) belong to the most abundant metals on Earth (see Table 1).

MAGMENT concrete consists of 87% magnetizable aggregates, which is a waste product arising from the manufacturing of ceramic ferrites and the recycling of electronic scrap. This material as well as the cement are provided by local suppliers thereby generating a very low CO_2 footprint. With a high permeability (up to 70), MAGMENT opens a broad range of electromagnetic applications and many possibilities for cost-leading and size-unlimited parts, since no pressing process is needed.

Fig. 1. MAGMENT magnetizable concrete.

Table 1. Elements in MAGMENT.

Chemical element	Abundance rank in magnetizable concrete	Abundance rank in the earth's crust
Iron	1	4
Manganese	2	12
Zinc	3	24
Calcium	4	5
Aluminum	5	3

Additionally, energy is saved during the processing of the concrete by:

- Using coarse aggregates (low crushing energy) as much as possible
- Processing of self-compacting concrete (no energy for densification)
- Requiring no heat treatment or sintering energy.

MAGMENT does not contain any ingredients exceeding concentrations dangerous to health according to legal regulations (like RoHS - 2011/65/EU).

The low material and manufacturing costs, and environmental friendliness of magnetizable concrete, together with its very good magnetics properties, give it the potential for truly widespread usage in power electronics applications. However, its main advantage is its ability to be fully integrated into any cement-based structure maintaining a high degree of robustness and high stability to environmental influences while achieving a prolonged lifetime.

This article presents an introduction to the material properties and characteristics of MAGMENT MC40, a specific formulation of magnetizable concrete, and discusses its usefulness in a number of major applications. These include power inductors, wireless charging systems (static and dynamic), inductive heating systems, and EMC filtering for HVDC power transmission systems. This article also introduces an online software tool that supports the development of custom magnetic components fabricated from MAGMENT.

Main Characteristics

Aggregate Sources

The attractive properties of soft magnetic ferrite ceramics can be extended by embedding them into a cement matrix. It allows shaping almost unlimited component geometries to optimize the magnetic field focusing in open magnetic circuits with a casting process performed under no pressure by using inexpensive raw materials obtained by recycling. The control of the right particle size distribution combined with a high ratio of ferrite particles offers magnetic permeabilities around μ_i = 40 and mechanical properties typical for concrete.

The ferrite aggregates can be obtained from scrap from ferrite manufacturing. With an annual production volume of 200,000 tons for soft ferrites, there are 12,000 to 16,000 tons of scrap available (with 6% to 8% rejects). Additionally, there are recycled electronic waste sources available with a potential annual volume of 40,000 tons. For higher demands, ferrite aggregates can be produced by inexpensive manufacturing lines using greater than two-thirds recycled iron oxides from steel mills following a proprietary process.

Processing

Magnetizable concretes can be mixed and processed by pre-casting or by site-casting. Ready-to-connect modules for test tracks are manufactured using the pre-casting technology. They contain all the charging relevant wiring including optional sensors. This allows the integration into existing road construction with minimal tolerances. An example application would be a charging module designed for embedding in the road (Fig. 2).

Fig. 2. Charging module for 22-kW wireless charger.

The combination of a high magnetic permeability, low losses and reasonable values of strength requires a density approaching of 3.75 g/cm^3. This is simultaneously an essential condition for achieving high thermal conductivity in the concrete. For charging applications, the heat transport is a vital property for removing the wire-related ohmic losses and the ferrite-related hysteresis losses.

For larger geometries up to few meters side length, the component can be supported by conventional concrete as a monolithic structure. Very similar thermal expansion coefficients allow the layer by layer arrangement. The material relevant properties can be seen in Table 2.

Table 2. Material data of the magnetizable concrete.

Parameter	Conditions	Unit	Value
Initial permeability	at 25°C	μ_i	40
Resistivity	dc	ρ [Ω m]	20
Density		γ[kg/m^3]	3750
Heat conductivity	at 25°C to 100°C	λ [W/(mk)]	3
Compressive strength	at 25°C	σ_C [MPa]	>50
Young's modulus	at 25°C	E_C [MPa]	25,000

Power Inductors

MAGMENT power inductors and transformers are based on a disruptive technology for both a novel material and an innovative magnetic design. MAGMENT's unique and outstanding properties allow the design of rugged inductive components (including a distributed air gap for minimized winding losses) by surrounding the coil with the MAGMENT material (Fig. 3). This ensures a complete magnetic filling of the available volume within the housing yielding maximum performance and cooling.

As compared to the conventional manufacturing of winding cores and sealing with a potting material, the flowability of our concrete materials allows a "wind and magnetic pour" process, which goes along with absolute shape and size flexibility. This allows one to both tailor components to minimize material utilization and to suit any given space constraints by a special magnetic design algorithm yielding lowest cost as compared to any other inductive technology.

Fig. 3. MAGMENT inductor with custom mounting-flange housing.

High demand from power electronics applications has sparked the development of both improved magnetic materials (e.g., powder cores, amorphous), winding technologies (e.g., copper foil, flat wire) and optimized core geometries. This has yielded a high refinement, pushing the limits of an otherwise conventional way of making inductive components. However, advancement in small steps maybe not enough to cope with the market expectations driven by the renewables revolution. Disruptive solutions such as magnetizable concretes are needed.

Dynamic Wireless Charging

Worldwide the adoption of electric vehicles (EVs) is gaining pace, bringing the charging infrastructure into focus. Apart from plug-in solutions the next step in the evolution of EV charging is wireless charging, which is perceived as an enabling technology for autonomous (self-driving) vehicles. Hence wireless charging holds its biggest promise in dynamic charging where the vehicle is charged while in motion (Fig. 4).

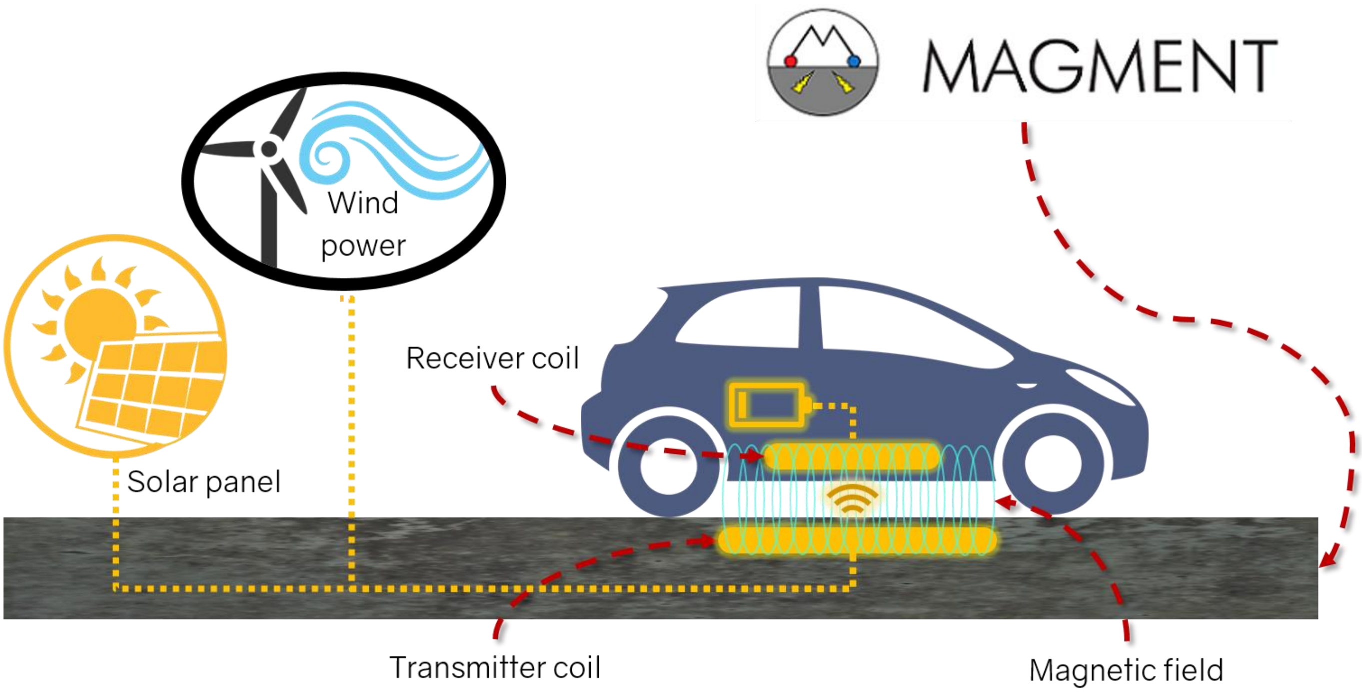

Fig. 4. Principles of dynamic wireless charging.

To do wireless charging of EVs with high efficiency, a focused magnetic field is required between transmitter and receiver, which necessitates a high magnetic permeability of the primary coil substrate. Magnetizable concrete proves to combine outstanding magnetic properties with high mechanical strength. It can be used equally for both static and dynamic charging. The advantage lies in the versatile shaping of the substrate to maximize transmission efficiency.

The magnetic properties of the concrete are generated by ferrite particles used as magnetic filler in the cement matrix. The magnetic material properties are characterized by high magnetic permeability and linearity as well as low losses. In addition, the concrete has high thermal conductivity, is mechanically stable and corrosion-resistant. The setting time as well as the hardening behavior are adjustable due to practical requirements.

Unlike wireless coils made with conventional soft-magnetic components, the winding can be integrated into the concrete and application-optimized solutions can be found with improved efficiency.

Component Design

The efficiency of power transmission between the road-based primary coil and the vehicle-based secondary coil is strongly dependent on component design, their arrangement and operating conditions. Numerous simulations were made to increase the efficiency via the coupling factor. The experimentally verified values of up to 96% efficiency for contactless charging are in the same range as the efficiency for conductive (wired) charging. The coupling factor k is a measure for the magnetomotive force conveyed from a primary to a secondary coil. This factor, along with the Q factor of the coils, determines the transmission efficiency (Fig. 5).

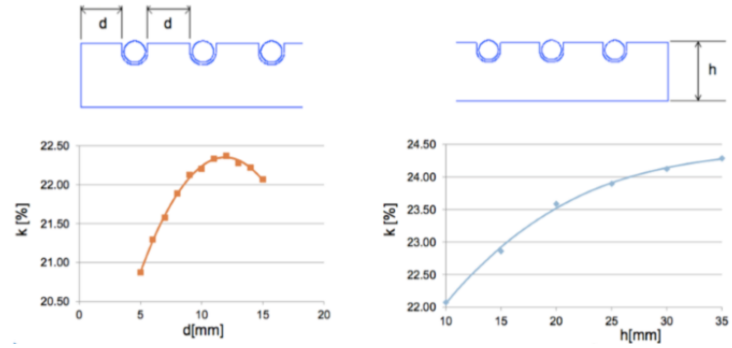

Fig. 5. Optimization of primary coil geometry for coupling factor k (patent pending).

The mechanical properties of charging modules must meet the following requirements:

- Fully integral into existing
  - roads
  - highways
  - bus stops
  - parking lots
  - buildings
- Highly durable
- Very cost efficient, no maintenance
- Vandalism proof
- Compatible with either concrete- or asphalt-based coating.

Verification of these properties will be carried out on test tracks under different traffic and climatic conditions.

Inductive Heating And Cooking

Induction heating provides contactless, fast, and efficient heating of conductive materials. This technology is nowadays the heating technology of choice in many industrial, domestic, and medical applications due to its advantages regarding efficiency, fast heating, safety, cleanliness, and accurate control. Fig. 6 lists the range of applications for inductive heating while Fig. 7 explains its principles of operation.

MAGMENT concrete cooking surfaces improve the user's experience while providing an efficient and cost-effective solution:

- Short heating cycles and high production rates
- Electromagnetic forces used with heating to stir or contain molten metal
- Fast and clean heating
- Energy savings due to selectivity and high efficiency
- Good control and repeatability
- Minimal or no surface oxidation and decarburization
- Lower distortions for surface or local hardening. See Fig. 8.

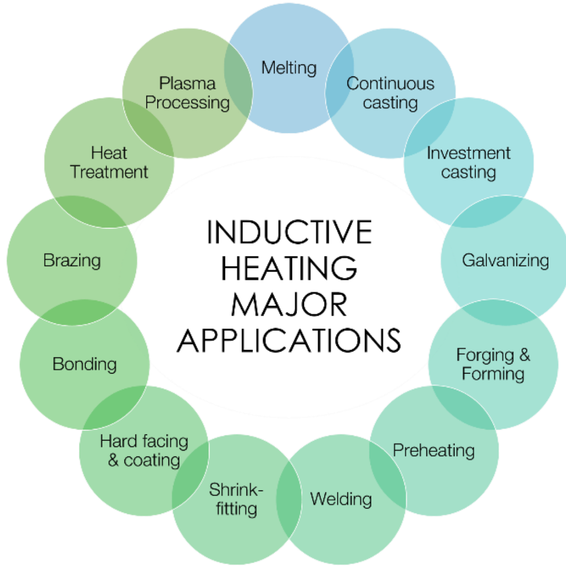

Fig. 6. Major applications for inductive heating.

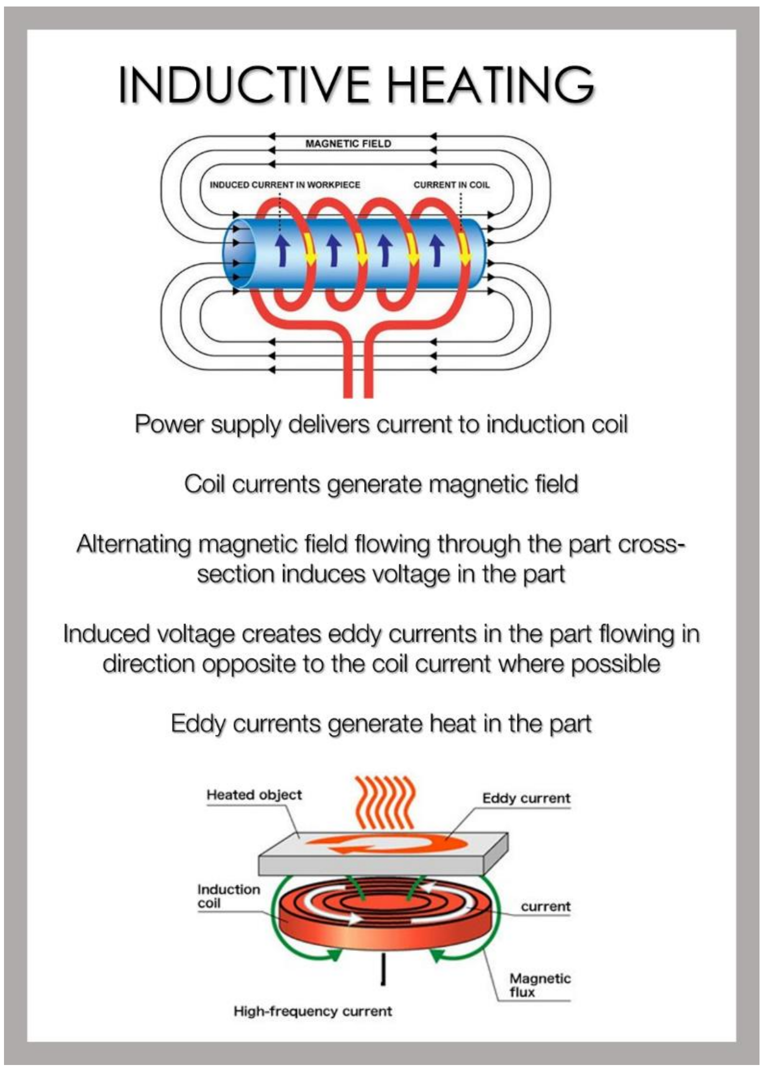

Fig. 7. How an inductive heating system works.

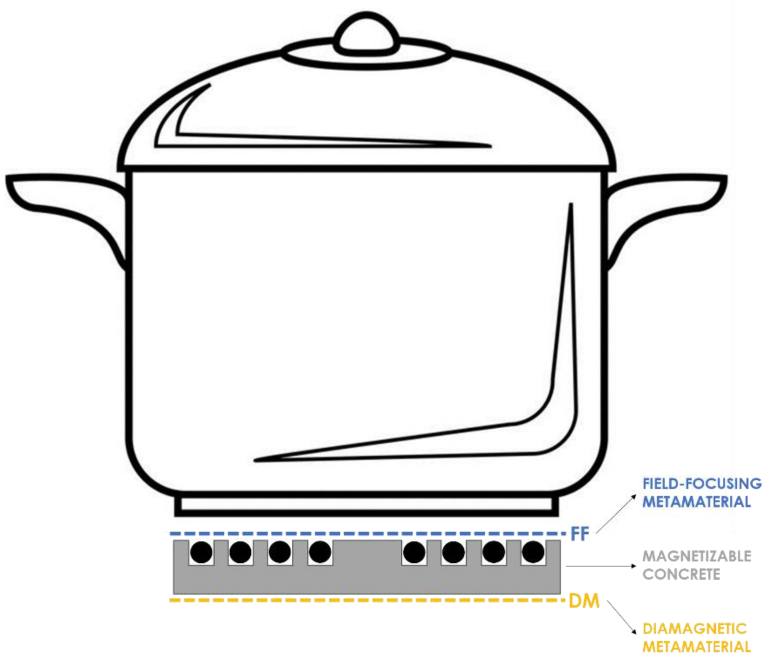

Fig. 8. Arrangement of materials for inductive cooking using MAGMENT.

EMC For Power Lines

Over long distances, high voltage direct current (HVDC) offers more efficient transmission of utility-level power than ac (Fig. 9). To mitigate electromagnetic interference (EMI) at frequencies in the low-frequency and medium-frequency bands, it is necessary to surround the transmission lines with magnetic materials to mitigate the radiation due to converter switching. This way the system meets the limits prescribed by CISPR standards.

A magnetizable concrete grade with the required capabilities is currently under development. The composite of a special magnetic filler embedded in the cement matrix has properties tailored for this application.

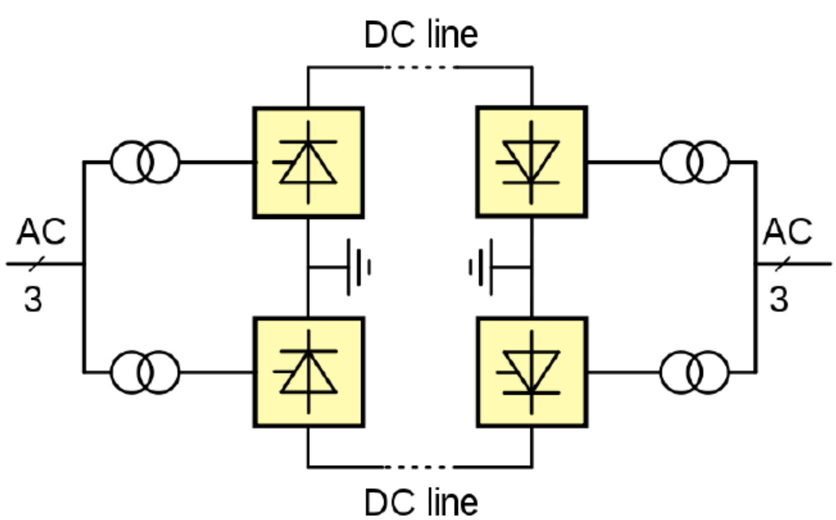

Fig. 9. Principle of HVDC long distance power transmission.

Compared to conventional magnetic materials such as powder cores currently in use, MAGMENT filters promise 35% lighter and 60% lower-cost EMI filters. Being a concrete, it offers a highly robust, cost efficient and in-situ castable solution to dramatically decrease installation costs.

Online Software For Custom Magnetics

The automated design process starts with the calculation of the MAGMENT inductor design parameters for the given target parameters (inductance, rated current and frequency) thanks to our innovative online software MAGMATH (Fig. 10). The design algorithm looks for the parameters giving the lowest material cost and hence the most compact design. The user can add any constraints to the ambient temperature, dimensions, losses or temperature rise to tailor the inductor to his or her precise needs.

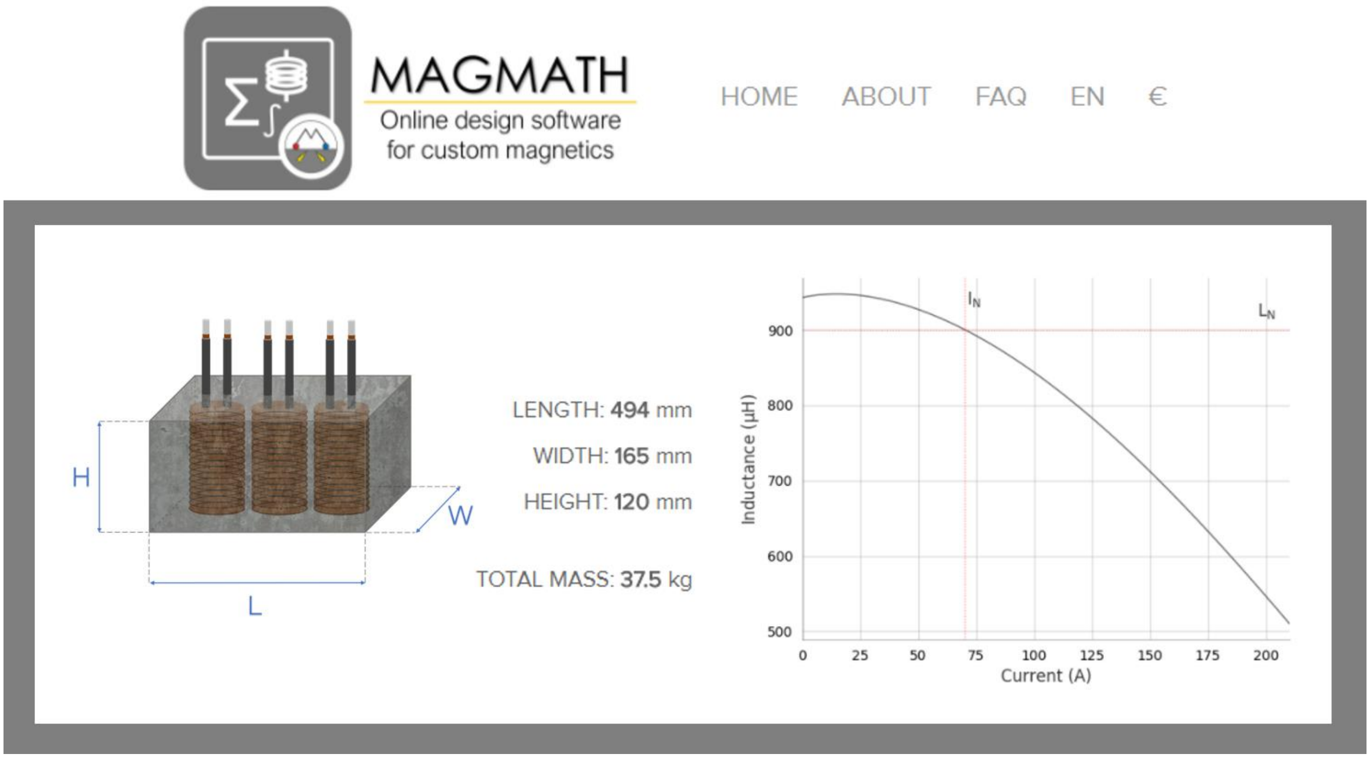

Fig. 10. MAGMATH software user interface.

The output of the software gives the inductance vs. current characteristic, the final dimensions, weight, total losses and operating temperature. Based on the output design parameters, a suitable coil former is chosen and the winding laid out. The housing containing the inductor is then designed according to the outer dimension of the MAGMENT material block (Fig. 11).

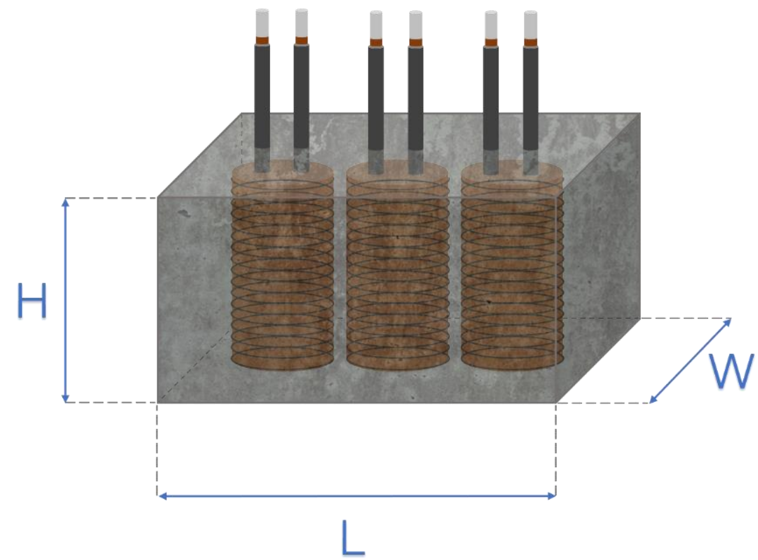

Fig. 11. Three-phase choke inductor.

The software also allows a 1:1 comparison with conventional soft magnetic materials (Table 3).

Table 3. Benchmark performed against three-phase conventional inductors.

L (µH)	I (A)	Size advantage	Weight advantage
2000	25	80%	65%
1000	50	69%	47%
900	70	54%	61%
400	120	55%	58%
300	540	73%	64%
120	1392	36%	23%

As previously described, MAGMENT cement-based inductors designed by MAGMATH have several advantages over conventional magnetics:

- Shaping freedom
- No size restrictions
- Tailoring of the electrical specification
- Lowest cost
- Short lead times.

The size and weight advantages obviously do result in even greater cost advantages. They are not only related to the lower material count (both magnetic and winding materials), but also to the ease of manufacturing. Unlike conventional magnetic materials, which for larger sizes imply the need of a laborious assembly, our inductors need simple windings placed in a mold and cast with magnetizable concrete. The resulting block gives a compact and robust component.

If required for larger sizes the material can be reinforced. Also, if free convection is not sufficient for heat removal, the device could also include forced (water) cooling. This may be necessary even though winding losses dominate and thermal conductivity of the magnetizable concrete is 3 W/mK, which is relatively high versus other potting materials.

Outlook

The magnetizable concrete MAGMENT MC40 presented in this article combines outstanding soft magnetic and mechanical properties. This innovative material consists of magnetizable ferrite particles, embedded in a cement matrix, allowing almost unlimited component geometries. Hence it is best suited for inductive power transmission to wirelessly charge EVs either statically or dynamically with low losses. This application is significant, because wireless charging is mandatory for the quickly developing autonomous driving applications.

The raw material basis of the magnetizable ferrite aggregates is almost unlimited since the elements it uses are among the most common in the earth's crust.

In terms of performance, there is a certain potential to further increase the magnetic permeability up to 70 by optimized packing density. The application related introduction of low-loss ferrites is essentially for further increased efficiency.

Finally, magnetizable concrete can help reduce the carbon footprint of soft magnetic materials. Ferrite scrap and/or recycled ferrite material is used for aggregates with a weight content up to 86% in the concrete. Optimized mixtures help further to reduce the cement content. It should be possible to approach a closed material circulation.

Several projects are being developed together with companies, governments and business partners. Solar-powered and wind-powered streets are our top attraction in Germany, while in Finland we are testing our streets in extreme weather conditions. As for our biggest partner, in China we are in the final stages of approval for a full bus rapid transit (BRT) system in several big cities in this country.

About The Author

Mauricio Esguerra is the CEO and co-founder of MAGMENT. Esguerra has more than 30 years of experience in the field of soft magnetic materials and its applications, modeling, testing, inductive components, power electronics and LED lighting. Prior to founding MAGMEBT, he held management positions at various companies including Siemens/EPCOS, Dialight, Pulse, Falco and Eglo. Esguerra is a member of IEC standard committees representing Germany and received the 1905 and 1906 awards. He is a lecturer at Hochschule der Bayerischen Wirtschaft in Munich, holds fourteen patents and has published 90 papers and a chapter of a book. Born in Bogotá, Colombia, Esguerra studied physics at TU München and Ohio State University.

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