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Bulk magnetic susceptibility measurements for determination of fly ash presence in concrete

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ABSTRACT

Reproducible measurements of magnetic susceptibility χ_m of laboratory and field extracted concrete core samples were achieved with simple instrumentation. There was a nearly linear relationship between χ_m and the mass of fly ash per unit volume, or its volume fraction. The magnetic response of a given FA was not significantly affected by the process of curing and subsequent evolution of the concrete over two years, or by carbonation of the concrete. Field extracted concrete cores exhibited a wide range of χ_m values. The group of specimens with the highest values of χ_m also had the lowest chloride ion diffusivity, consistent with the presence of admixed FA. Conversely, specimens with nil magnetic response included those from concrete with the highest chloride diffusivity. The magnetic measurements provided reasonable order-of-magnitude indications of FA presence in field extracted cores. However, precise determination of FA content from magnetic measurements of field cores does not appear feasible in the absence of additional information.

1. Introduction

1.1. Background

Concrete with about 20 to 30% fly ash (FA) of cement replacement has shown excellent resistance to chloride ion penetration, as manifested by observations of low apparent chloride diffusion coefficients which also tend to decrease as concrete ages [1]. There is considerable interest to obtain further evidence of this type from structures in service, and use the resulting information to optimize future mixture proportioning for durability. However, records on mixture proportioning of field structures are not always available, leading to the need to examine concrete samples for evidence of FA presence. Petrographic confirmation of the presence of both residual fuel particles and glassy cenospheres can be conclusive evidence of FA presence [2]. Nevertheless, those features are often not clearly observable, and after prolonged aging, the pozzolanic reaction products may not be clearly differentiated from hydration products from ordinary Portland cement (OPC) [3]. Additionally, even when petrography confirms the presence of FA, its content cannot be reliably quantified. This paper examines the use of non-destructive magnetic measurements as an alternative to provide semi-quantitative indication of the amount of admixed FA in field-extracted concrete samples.

1.2. Fly ash and magnetic detection

FA is retrieved from the emission control systems of coal-fired utility boilers and contains a fraction of the mineral content of the coal. Some of these minerals are iron oxides (customarily reported as Fe_2O_3), which make up from 3 to 30% of FA used in concrete. The iron oxide in most FA contains a significant ferrimagnetic fraction [3–12], expected to be either magnetite (Fe_3O_4, or more properly Fe_2O_3–FeO), or maghemite (γ-Fe_2O_3). The magnetite may have varying degrees of iron substitution by Mg or other species. Dekkers [7] found a negligible amount of iron substitution, whereas Kukiera et al. [12], Hulett [13] and Gomes et al. [14] reported a highly substituted magnetite spinel in FA. The major magnetic portion of FA used in concrete has a particle size from 5 µm to 30 µm [2,3]; most particles of FA are also in this size range. OPC also contains iron oxides, usually less than 5% [3]. However, only a small fraction of those oxides exhibits ferromagnetism [15,16].

The magnetic characteristics of the compounds present in FA and the compounds formed from high-alumina cement have been used sometimes to characterize concrete. Farrell et al. [17] reported that concrete acquires natural remanent magnetization (due to the earth's magnetic field) at casting and presented measurements of the direction and intensity of magnetization in concrete samples with and without FA. The intensity was one order of magnitude greater in concrete with 10% FA (as cement weight replacement) than with no FA. The magnetization direction in concrete with FA corresponded to that of the earth's magnetic field, but less agreement was observed for concrete with no FA. A linear relationship was found between the measured magnetization intensity and the percentage of FA admixed

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Table 1
Chemical composition (wt.%) and magnetic material content (fraction) of FA1 and FA2

	FA1	FA2
SiO_2	52.0	49.4
Al_2O_3	27.6	27.5
Fe_2O_3	6.2	8.5
CaO	1.7	1.7
MgO	0.8	0.9
SO_3	0.4	0.5
Na_2O	0.3	0.3
M	0.034	0.051

in cement paste. Another investigation [18] employed the output of a magnetic steel locator (in the absence of steel) to detect not the presence of FA, but the use of high alumina cements (HAC). The magnetic steel locator served to provide a rough indication of the magnetic susceptibility of the concrete, indicative of the hydration products formed from ferrous oxides present in HAC. Arroyo [19] also used a magnetic force method. Those results suggested the possibility of using either magnetization or magnetic susceptibility as a means to detect the presence of FA in hardened concrete.

1.3. Magnetic behavior of particle dispersions

Magnetic properties are routinely measured in the geological study of rocks, by methods easily extended to detect mineral admixtures in concrete. The induced magnetization (**M**, the magnetic moment per unit volume [20]) in a uniform medium may on first approximation be considered to be proportional to the magnetic **H** field [20]:

$$\boldsymbol{M} = \chi_{\mathrm{int}} \boldsymbol{H} \tag{1}$$

where χ_{int} (nondimensional) is the intrinsic magnetic susceptibility of the medium. Consider now a composite medium consisting of a dispersion, in a non-magnetic matrix, of microscopic individual magnetizable particles each with susceptibility χ_{int}. Under simplifying assumptions [21] (i.e., same-size spherical particles uniformly distributed in space), the composite medium is expected to behave macroscopically as a uniform medium having a susceptibility χ_{m} (measured susceptibility, playing macroscopically the same role as χ_{int} in Eq. (1)) given by

$$\chi_{\mathrm{m}} = V_{\mathrm{f}} \chi_{\mathrm{int}} (1 + N \chi_{\mathrm{int}})^{-1} \tag{2}$$

where V_{f} is the fraction of the composite volume occupied by the particles and N is a demagnetization factor [22,23] depending on the shape of the particles. For ideally spherical particles, N is 1/3, while values of N=0.25 to 0.31 have been proposed for actual magnetite particle distributions [24]. With rocks containing magnetic particle dispersions, Eq. (2) was approximately verified in experimental studies [24,25]. More complex relationships (involving fractional power dependence with V_{f}) have been proposed for a variety of systems [24,25]. The ratio $\chi_{\mathrm{m}}/V_{\mathrm{f}}$ is also known as the effective magnetic susceptibility χ_{eff}.

In a macroscopically heterogeneous medium such as concrete, quasi-homogeneity at a meso-scale may be assumed, where the meso-χ_{m} value is the average over a relative small volume. From several of these meso-χ_{m} values an average can be calculated, and this average then can be considered the χ_{m} of the medium.

The value of χ_{m} has been determined for spaces filled with class "F" FAs [7] and for synthetic magnetite embedded in a non-magnetic matrix [26]. For several European class "F" FAs, Dekkers and Pietersen [7] measured both χ_{m} and saturation magnetization, supplemented by quantitative X-ray diffraction (XRD) analysis and thermomagnetic analysis. The iron oxide content of these FAs varied from 3 to 12% by weight. The saturation magnetization results indicated that the magnetic portion resided in a low-substitution magnetite spinel, and that 20 to 50% of the total iron oxides was magnetite. The hematite content detected by XRD in the same samples was less than 0.5%. Other authors [2,6] have reported hematite (α-Fe_2O_3) (by XRD) from 4 to 10% by weight in FA. Since χ_{int} of hematite is two to three orders of magnitude smaller than that of magnetite, the effect of hematite on χ_{m} of FA remains negligible in comparison. It may then be considered that the magnetic response of FA is essentially due to magnetite or maghemite. Iron substitution (e.g., by Mg) in magnetite may also lead to a reduction of magnetic susceptibility by as much as 60% [12] when compared with that of non-substituted magnetite.

Mauritsch et al. [26] reported χ_{m} values, obtained from synthetic magnetite of various particle sizes and volume fractions embedded in a non-magnetic matrix. For a given particle size, an approximately linear dependence was found between χ_{m} and the magnetic particle volume fraction. Mauritsch et al. also found that the χ_{m} value varied (weakly) with the magnetic particle size, when samples with the same magnetic volume fraction were compared.

1.4. Objective and approach

This investigation was conducted to assess the applicability of magnetic methods for determining FA presence and content in hardened concrete. To that effect, a susceptometer to measure χ_{m} of concrete samples was constructed, and used to characterize the magnetic response of laboratory specimens and samples from field structures.

2. Experimental

2.1. Laboratory specimens

Two different class "F" FAs, designated FA1 and FA2 (used in an investigation of concrete carbonation [27]) were used to prepare laboratory specimens of dry powder mixes, mortar, or concrete. All specimens were cylindrical to match the shape of the concrete core samples extracted from field structures. Table 1 shows the chemical composition of both FA1 and FA2, determined by X-ray fluorescence. Also shown is the magnetic material mass fraction (*M*) of each FA, measured with a procedure similar to that described by Fernandez [28]. In that procedure, a slurry of the FA is agitated by a polymer-coated stirring magnet. The mass picked up by the magnet is expressed as a fraction of the total mass of FA in the slurry.

2.1.1. Dry mix specimens

Seven dry mixes of FA in an Ottawa silica sand (size 50–70) matrix were prepared, with various amounts of mass of FA per unit volume (M_{V}) as shown in Table 2. The sand and FA were mixed until a uniform color was obtained. An additional blank sample contained only sand. Plastic and cardboard cylindrical shells 125 mm to 150 mm long contained the dry mixes. The internal diameter of the shells was ~41 mm.

2.1.2. Mortar specimens

Mortar specimens were prepared with Ottawa sand and cementitious material (OPC (Type I) and FA), with a water to cementitious mass ratio (w/cm) of 0.5. The specimens had varying amounts of FA1

Table 2
Dry mix proportions (kg/m^3)

	FA type and mix designation						
	FA1		FA2				
	A	B	C	D	E	F	G
M_{V}	1000	450	940	360	180	90	45
Sand	0	1350	0	1440	1620	1710	1755

Table 3
Mortar mix proportions (kg/m^3)

	Mix designation				
	H	I	J	K	L
M_V (FA1)	45	90	180	270	315
OPC	405	360	270	180	135
Sand	1350	1350	1350	1350	1350
Water	225	225	225	225	225

w/cm = 0.5 for all mixes.

and were cast in duplicate. The cementitious proportion found in concrete was simulated by using a 3:1 sand to cementitious mass ratio. The mix proportions are given in Table 3. The specimens were cylinders 41 mm in diameter by 100 mm to 125 mm in length. After casting, the mortar specimens were demolded and kept in a chamber at 95% to 100% relative humidity for a period exceeding two years. During that period, the specimens were periodically removed briefly from the chamber for magnetic measurements and returned immediately afterwards.

2.1.3. Concrete specimens

These specimens were segments 50 mm to 60 mm long cut from laboratory concrete cores originally 75 mm diameter by 150 mm long (3 in by 6 in). The specimens were four years old and had been used as part of a concrete carbonation investigation [27]. The concrete specimens contained FA1, in amounts equal to 35% and 50% of the total cementitious material. The fine aggregate was sand and the coarse aggregate was limestone (9.5 mm maximum size). The concrete mix proportions are given in Table 4. The specimens were from a population that had been exposed to a CO_2-rich atmosphere for various amounts of time, creating fully carbonated zones that extended radially from the surface to carbonation depths designated by X_C. For each mix, three specimens were selected so that they each had carbonation depths 4 mm < X_C < 5 mm, 9 mm < X_c < 12 mm, and 28 mm < X_c < 38 mm respectively.

2.2. Field concrete specimens

One hundred and eighty cylindrical concrete cores were examined. These cores were extracted in a separate investigation from the substructures of 29 Florida marine bridges [29], at elevations ranging from 0 to 3 m above high tide. The concrete composition of all samples from a given bridge was expected to be approximately the same. The coarse aggregate was nearly always limestone, with a typical maximum size of 30 mm. The diameter of each concrete core was ~43 mm and the length ranged from 50 mm to 200 mm. All these samples were in contact with laboratory air (average relative humidity ~70%) for at least 3 years before the tests described here were performed, so the concrete was dry and usually carbonated to a depth of several mm. Values of apparent chloride diffusion coefficient (D_{app}) are available [29] from analysis of additional cores extracted simultaneously and at similar elevations from the same bridges.

Table 4
Concrete mix proportions (kg/m^3)

	Mix designation	
	M	N
M_V (FA1)	156	223
OPC	290	223
Water	165	165
Sand	627	607
Coarse aggregate	989	988

w/cm = 0.37 for both mixes.

2.3. Susceptometer

The operation of this device is based on the force that a sample with magnetic susceptibility experiences when placed in a magnetic field gradient. The device is shown schematically in Fig. 1 and resembles that described by Davis [30–32]. Additionally, the apparatus conceptually relates to the Rankine balance [33], in which a force is measured between a magnet and a sample placed in proximity to the magnet. For an ideal magnetic dipole of moment m placed at a distance Z_O from a semi-infinite sample of magnetic susceptibility χ_m, an attraction force F develops given by:

$$F = \frac{3\mu_0 m^2 \chi_m}{64\pi Z_0^4} \tag{3}$$

where $\mu_o = 4\pi \times 10^{-7}$ N s^2/C^2 is the magnetic permeability of open space.

Davis indicated that Eq. (3) was reasonably accurate in practice for small magnets placed near a homogeneous sample at least 3 times larger than the magnet. A practical compromise between conveniently-measured force, size of sampled region (to average out heterogeneities, introduced by the presence of aggregate) and easily reproducible sample-magnet distance, was achieved by using a moderate-sized magnet. The magnet was actually an assembly of two individual ceramic magnets (each 25.4 mm wide by 19.1 mm deep and 4.5 mm high, magnetic axis along the shortest direction) stacked atop each other. The two individual magnets making up the assembly were assumed to have the same magnetic moment. Employing a procedure similar to that of Davis [30] each magnetic moment was determined to be 0.43 A m^2, for a nominal composite magnet moment m = 0.86 A m^2.

A modern top-loading balance (Sartorius AG-Gottingen, LC3201D), with a capacity of 3200 g and a sensitivity of 1 mg was used. The balance was a production model with no modifications. The magnet was positioned ~80 mm above the balance plate by an aluminum stand rod mounted on a polymer base. An austenitic stainless steel screw movement allowed fine adjustment of the magnet height. A round PVC cradle held in position the cylindrical test samples, so that their axes were perpendicular to the magnetic field axis of the magnet, and centered as shown in Fig. 1. A hole drilled in the center of the cradle accommodated a precision spacer temporarily positioned to adjust the cradle position so that the distance between the top of the magnet and the bottom of the sample was 10 mm ± 0.1 mm. Adjustment was necessary only when reassembling the susceptometer whenever the balance was used for other purposes between magnetic measurements. Each F measurement was the average of 4

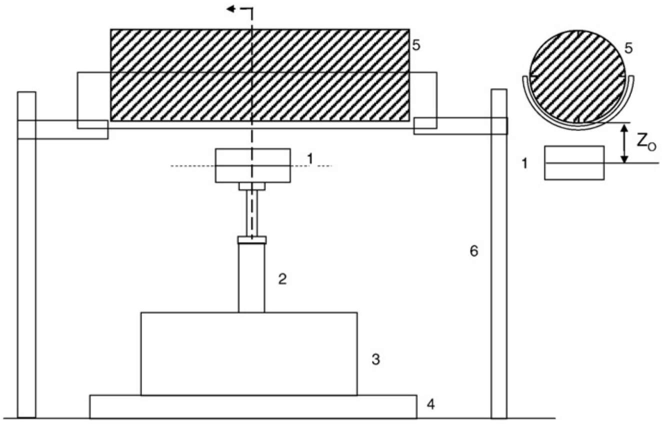

Fig. 1. Susceptometer 1) magnet assembly, 2) aluminum rod, 3) polymer base, 4) balance plate, 5) concrete sample, 6) sample stand. Components not to scale.

Table 5
Correction factors (C_F) found experimentally

Sample diameter (mm)	C_F
41	1.27
45	1.21
51	1.13
64	1.05
76	1.00

readings. The first was obtained after placing the sample on the cradle. The following readings were obtained each after consecutively rotating the sample 90° about its axis in the same direction.

Initial tests with 41 mm diameter samples of the same material showed that force measurements were not affected (within the resolution of the balance) by the cylinder length as long as it exceeded ~70 mm, which was the case for all the laboratory specimens and over 95% of the field samples. Changes in sample diameter moderately affected the resulting force. However, the force became nearly constant after the sample diameter exceeded ~64 mm. This was concluded from a series of tests conducted with 70 mm long cylinders of varying diameters, filled with FA1. Accordingly Eq. (4), which was derived from Eq. (3) to calculate χ_m from the force measurements, incorporates a diameter correction factor C_F.

$$\chi_m = \frac{64\pi Z_0^4 F}{3\mu_0 m^2} C_F \tag{4}$$

The values of C_F as determined from the variable diameter tests are listed in Table 5. Interpolation to adjust for the actual sample diameter was performed as needed.

3. Results and discussion

3.1. Sampling effects

For all the experimental conditions examined, the forces that developed between the sample and the magnet were $\leq 10^{-3}$ N ($\leq$100 mg indication), corresponding to $\chi_m \leq 0.01$ for the typical sample and spacing dimensions used. These values are in agreement with the expected amounts of magnetic material present in FA and with the sample compositions and sizes used [34,35]. On any given laboratory specimen (dry mixes, mortar, concrete with small coarse aggregate), the four force measurements taken 90° apart showed little variation (typically <5%) from each other. However, for the concrete specimens extracted from field structures, there was significant force change (by as much as 30%) as the specimen was rotated. This variability is likely to reflect the random presence of the larger coarse aggregate particles (which had a maximum size comparable to the specimen diameter) on the side facing the magnet. For the typical sample sizes and sample-to-magnet distances used here, the lowest measurable value of χ_m was ~2–3 × 10^{-5}, corresponding to the 1 mg resolution of the balance as reflected through Eq. (4).

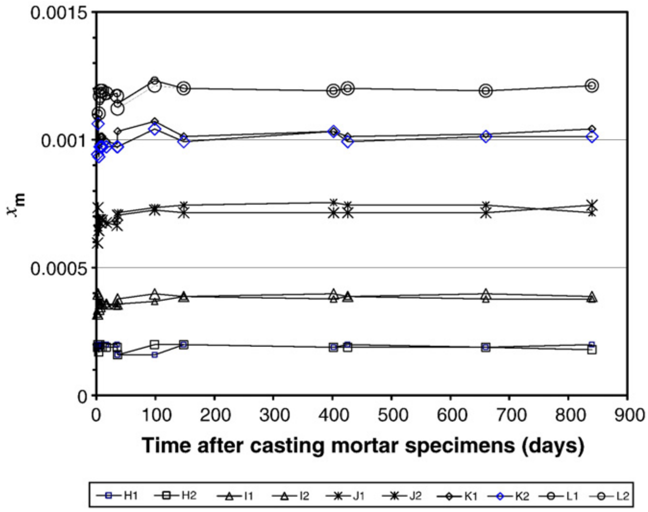

Fig. 2. Evolution of χ_m with time for mortar samples. Results from replicate specimens. See Table 3 for description.

3.2. Reproducibility and time evolution

Fig. 2 shows the χ_m values of the mortar samples obtained during the first ~2 years after casting, while the samples were kept in a chamber at 95% to 100% relative humidity. At any given time there was generally good reproducibility when testing duplicate mortar samples; typical variation was $\Delta\chi_m$ ~ 2 × 10^{-5}, effectively determined by the balance resolution. Measurements conducted at different times normally involved reassembling the susceptometer, with consequent variation of Z_O within its tolerance (0.1 mm, or 1%). Since per Eq. (4) $F \propto Z_O^{-4}$, a corresponding scatter of ~4% could be expected and was often observed between consecutive measurements.

Within the experimental resolution available, Fig. 2 revealed no consistent short- or long-term trend of variation of χ_m with time. This result suggests that the hydration reactions did not affect markedly the magnetic properties of the particles responsible for the magnetic response.

3.3. Effect of concrete carbonation

Table 6 shows the χ_m values measured for the carbonated concrete samples with various carbonation depth ranges. These results show that χ_m was little affected by the depth of the carbonated zone. The low sensitivity to carbonation, and to curing time as shown earlier, suggests that the magnetic response of concrete should change little as a structure ages. These findings are not surprising as magnetite should be stable in highly alkaline media (non-carbonated concrete pore water) and also under the neutral-slightly alkaline environment expected to exist in carbonated concrete [27]. This lack of sensitivity to carbonation is encouraging for the use of χ_m tests to detect the presence of admixed FA, as near-surface carbonation often affects laboratory samples.

3.4. Dependence of magnetic response on fly ash content

The results in Fig. 2 show that χ_m increased when testing mix types H to L, which in that order had increasing FA2 content. To compare that result with those of other specimens, it is desirable first to normalize for variations in the magnetic material content of each FA. An attempt to account for that variation can be made by assuming for simplicity that all the magnetic material in each FA (present to the extent measured by M) is solid magnetite. Thus, an estimated

Table 6
χ_m for concrete specimens with various carbonation depths

X_C range (mm)	Mix designation			
	M		N	
	Mean	SD	Mean	SD
4–5	$7.2 \cdot 10^{-4}$	$0.31 \cdot 10^{-4}$	$10.0 \cdot 10^{-4}$	$0.47 \cdot 10^{-4}$
9–12	$6.5 \cdot 10^{-4}$	$0.32 \cdot 10^{-4}$	$9.8 \cdot 10^{-4}$	$0.41 \cdot 10^{-4}$
28–38	$6.8 \cdot 10^{-4}$	$0.47 \cdot 10^{-4}$	$9.7 \cdot 10^{-4}$	$0.44 \cdot 10^{-4}$

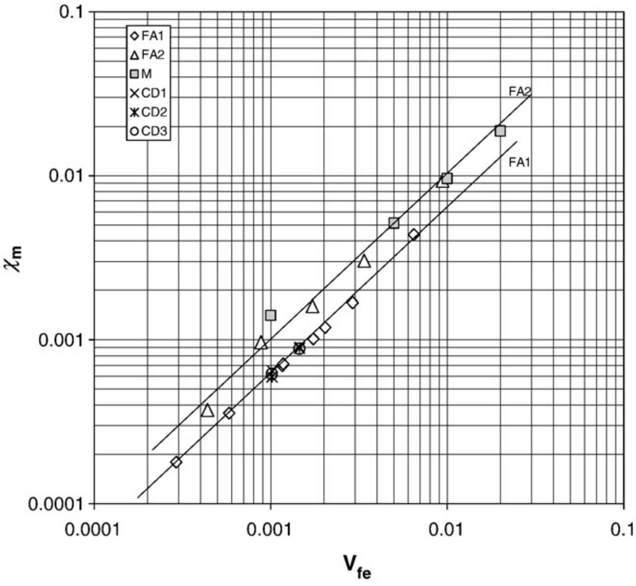

Fig. 3. χ_m vs estimated magnetite volume fraction, grouped by FA type, for laboratory specimens of mortar, concrete (labeled by carbonation range) and dry mixes. Series "M" is data from Mauritsch [26] for synthetic magnetite in an inert matrix.

magnetite volume fraction (V_{fe}) was defined as follows for each of the mixes tested:

$$V_{fe} = MM_V / \delta_M \tag{5}$$

where δ_M is the density of magnetite, $5.2 \cdot 10^3$ kg/m^3 [25].

Fig. 3 shows χ_m as function of V_{fe} for the results from the laboratory specimens. The results have been grouped by whether FA1 or FA2 was present. For the mortars and concrete, the data represent the average of results of duplicate specimens for ages >100 days, and the averages of the three carbonation ranges respectively. The FA1 series for dry mixes, mortar or concrete fall closely along a common straight line, indicating that the magnetic response was mainly a function of the amount of FA1 per unit volume regardless of the chemical environment or history. The common line was drawn with a slope of 1 in the log–log graph, to reflect that χ_m varied nearly linearly with M_V. The FA2 series (available only for mortar) also fits closely a nearly linear dependence with M_V. However, the lines for both FAs are distinctly separated by an ~1:1.7 ratio, indicating that the idealization implied in Eq. (5) is not fully warranted for at least one of the FA examined.

For comparison, Fig. 3 also includes results reported by Mauritsch [26] for dispersions of synthetic magnetite in an inert matrix, where Eq. (5) should apply closely. The sizes of the magnetite particles used in those experiments (<40 µm) were comparable to those usually found in FA [14,35], and the magnetite concentrations were on the order of those estimated for the specimens tested here. The Mauritsch results show some deviation from linearity, but otherwise follow quite closely the trend observed for FA2 so that the magnetic material of the latter appears to act much like the particles of synthetic magnetite. In general, however, the particles acquired by the stirring magnet in the test to measure *M* are expected to have inert inclusions, and to contain some magnetic material with Fe substitution. Thus, V_{fe} is likely to be an overestimate. In the case of FA1, those overestimating factors may have been more important than for FA2, thus shifting the FA1 trend line to the right. It is also noted that the effective magnetic susceptibility calculated from the χ_m and V_{fe} trends in Fig. 3 is $\chi_{eff}=1$ for both FA2 and the material tested by Mauritsch, and $\chi_{eff}=0.6$ for FA1.

3.5. Field concrete chloride diffusivity, magnetic response and fly ash presence

Fig. 4 shows in the *y*-axis the D_{app} values measured on 29 Florida bridges [29], and in the *x*-axis the corresponding χ_m values. The χ_m value of each bridge was obtained by averaging the χ_m values from all the samples corresponding to that bridge. Within a given bridge the samples were usually of the same type of concrete as they were obtained from comparable structure elements and elevations.

There was distinct correlation between the magnetic signature and diffusivity trends. For ten of the bridges all, or nearly all of the samples had force readings below the sensitivity limit and correspondingly low χ_m ($<\sim 10^{-5}$) values; those results are grouped on the left edge of the graph. The corresponding D_{app} values were all $>10^{-12}$ m^2/s, including the bridges with the five highest D_{app} values ($>10^{-11}$ m^2/s) of the entire population. At the other extreme, all the eleven bridges with $\chi_m > 5 \times 10^{-4}$ had the eleven lowest diffusivity values ($D_{app} < 10^{-12}$ m^2/s). An intermediate group of eight bridges had $5 \times 10^{-5} < \chi_m < 5 \times 10^{-4}$ and diffusivity values intermediate of those in the other two groups.

As documented elsewhere [29] the bridges in the group with the highest D_{app} values were built with concrete with cement not blended with FA, consistent with the absence of magnetic signal indication here. In contrast, some of the bridges in the group with very low D_{app} were known to have been built using cement blended with significant amounts (e.g., 20%) of FA, in agreement with the high values of χ_m observed for that group. Information on cement blending for the rest of the bridges in the low D_{app} group was not available, but the combination of low diffusivity and high χ_m strongly suggests that FA was used in those as well. While high, the χ_m values in this group of bridges span a range of about one order of magnitude which may reflect not only variations in the extent of cement blending but also different ranges of magnetite content of the FA, the degree of iron substitution present in the magnetite, the χ_{int} value of the magnetite, and the magnetite particle size and shape.

The intermediate susceptibility–diffusivity group might have had cases where cement was blended with a sizable amount FA of low magnetite content, but that does not appear to be likely as a high FA content is expected to have resulted in markedly reduced diffusivity.

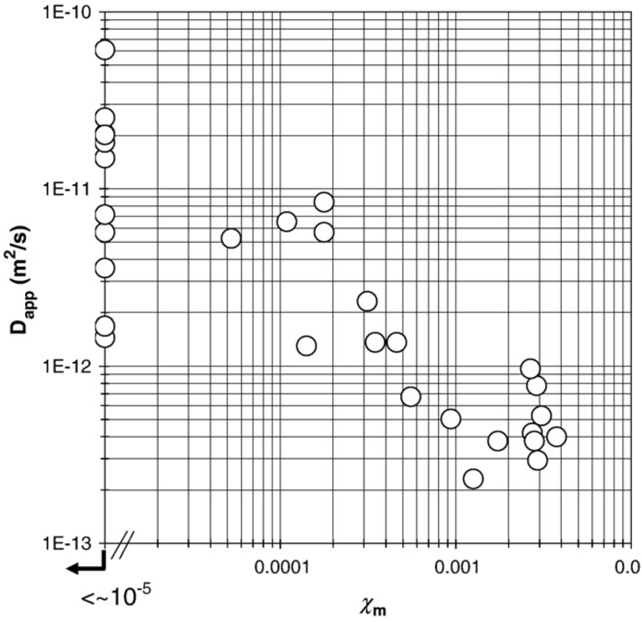

Fig. 4. D_{app} and χ_m (averaged for each bridge) of concrete core samples extracted from the substructure of 29 Florida bridges.

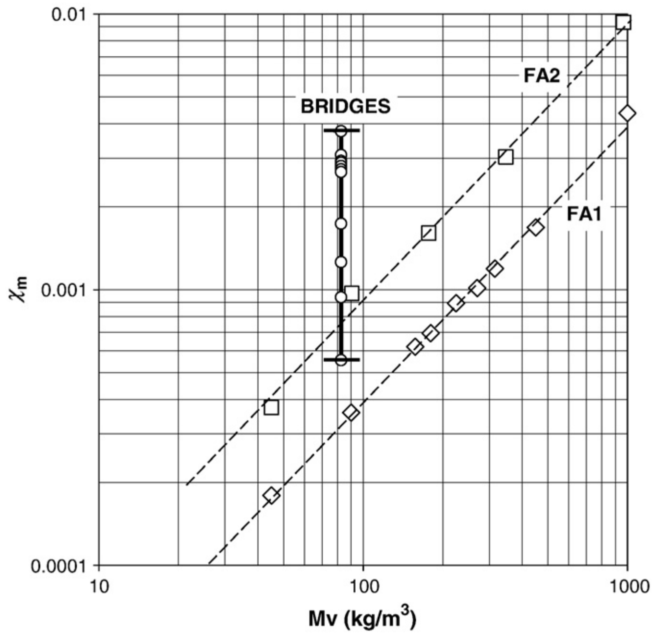

Fig. 5. χ_m and M_V for laboratory (FA1, FA2) and low-D_{app} bridge concrete samples.

Instead, this group may have contained cement or aggregate with small amounts of magnetic material. Small but detectable χ_m values in the absence of FA have been reported by Fernandez [28] and Musikas [34], for cements containing residual magnetite amounts. Likewise χ_m values in the range 2×10^{-5} to 2×10^{-4} have been observed also by Dortman [24,36] for rock samples with 10^{-2} to 10^{-5} vol.% of magnetite equivalent.

3.6. Magnetic response and amount of fly ash in field concrete

Fig. 5 shows χ_m values for laboratory (FA1, FA2) and field concrete samples (averaged per bridge) for the bridge group that exhibited the low chloride diffusivity ($D_{app}<10^{-12}$ m^2/s) and high χ_m combination noted above in discussing Fig. 4. The mass per unit volume (M_V) of FA in kg/m^3 is used in the abscissa to permit comparison with the FA content of the cement in the bridges. For those M_V was assigned a generic range from 70 kg/m^3 to 97 kg/m^3, corresponding to a nominal content of 18% to 22% FA Class "F" in concretes with cementitious factors of 388 kg/m^3 to 444 kg/m^3 often specified by the Florida Department of Transportation (FDOT) for low elevation marine bridge substructure [37]. The figure shows that, when expressed as function of M_V, the magnetic response of each laboratory FA follows individually a nearly linear trend with M_V. However, the differences in M and estimated χ_{eff} between the two materials combine to produce a ~3:1 difference in their respective χ_m values for a given value of M_V. For their part, the χ_m for the bridges range from values comparable to the average of FA1–FA2 values, to ~5 times greater than the FA2 value. This disparity may indicate that some of the bridges had a much higher FA cement replacement than estimated here. However, given the variability observed between the FA1 and FA2 materials the higher χ_m values seen in the bridge samples may also reflect a generally richer magnetic particle content of the FA used there, particles with greater χ_{eff}, or a combination of those factors. Thus, the magnetic measurements provided reasonable order-of-magnitude indications of FA presence but precise determination of FA content does not appear feasible without additional input. Since the individual χ_m–M_V trends showed good correlation, one such input for precise determination of FA content could be provided by calibration against archival samples of the FA used during construction, should those be available.

4. Conclusions

- A clearly defined magnetic response could be measured in fly ash (FA) containing laboratory dry mixes, cements and concretes. Reproducible measurements of magnetic susceptibility χ_m of laboratory and field extracted concrete core samples were achieved, over a wide response range, using simple instrumentation. Correction factors were developed to normalize the results for sample shape and size.
- There was a nearly linear relationship between χ_m and the mass of fly ash per unit volume, or its volume fraction. There was considerable difference in the magnetic response of samples of fly ash from different sources. However, the magnetic response of a given FA was not significantly affected by the process of curing and subsequent evolution of the concrete over two years, or by carbonation of the concrete.
- Field extracted concrete cores exhibited a wide range of χ_m values. The group of specimens with the highest values of χ_m also had the lowest chloride ion diffusivity, consistent with the presence of admixed FA. Conversely, specimens with nil magnetic response included those from concrete with the highest chloride diffusivity.
- The magnetic measurements provided reasonable order-of-magnitude indications of FA presence in field extracted cores. However, precise determination of FA content from magnetic measurements of field cores does not appear feasible in the absence of additional information such as calibration against archival samples of the same FA.

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Glossary

$\mathbf{M}$: Magnetic moment per unit volume.
$\mathbf{H}$: Magnetic field.
χ_{int}: Magnetic susceptibility of a uniform material.
χ_{m}: Measured susceptibility at the macroscopic scale.
V_{f}: Volume fraction occupied by magnetic particles.
N: Demagnetization factor.
χ_{eff}: Effective magnetic susceptibility $=\chi_{\mathrm{m}}/V_{\mathrm{f}}$.
M: Mass fraction of magnetic material in FA.
M_{V}: Mass of FA per unit volume.
X_{c}: Carbonation depth.
D_{app}: Apparent chloride ion diffusion coefficient.
μ_{o}: Magnetic permeability of open space.
m: Magnetic dipole moment.
F: Attraction force.
Z_{o}: Distance between dipole and semi-infinite sample.
C_{F}: Diameter correction factor.
V_{fe}: Magnetite volume fraction.
δ_{M}: Density of magnetite.