Compacted and Spheroidal Graphite Irons: Experimental Evaluation of Poisson's Ratio

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Spheroidal Graphite cast Iron (SGI), also known as ductile iron, represents a perfect material for a very large range of modern applications. It is successfully used wherever optimal strength, stiffness and even low costs are required: high values of tensile strength and Young's modulus are between its most appreciable properties. At the same time, nowadays, a different cast iron, known as Compacted Graphite Iron (CGI) or vermicular graphite iron, is taking the first steps in replacing SGI respect to some specific applications. It depends on a better castability, machinability and thermal resistance. CGI is an ideal cast iron in the case of components under simultaneous mechanical and thermal loadings, such as cylinder blocks and heads. Unfortunately, while SGI benefits of a wide scientific literature, CGI is a relatively unknown material. Moreover, dut to its particular microstructure, the production of CGI presents additional difficulties and it is not easy to obtain stable properties in the CGI alloy. This paper illustrates a way for the experimental evaluation of the Poisson's ratio by tensile specimens, comparing this propriety in the case of SGI and CGI.

***Keywords**: Foundry, Cast Iron, Tensile Test, Experimental Mechanics*

1. INTRODUCTION

Although Compacted Graphite Iron (CGI) was first observed in 1940s, an unstable foundry production precluded its use for high volume production until advanced process control technologies became available [1-3]. Nowadays CGI is used for complex shape applications such as cylinder heads and engine blocks. As the demand for higher torque, lower weight and, consequently, lower emissions continues to grow, engine designers are forced to seek stronger materials with higher heat transfer efficiency. This is particularly true in the diesel sector where resolution of the conflicting performance objectives requires increased cylinder bore pressures. At these operating levels, the strength, stiffness and fatigue properties of traditional cast iron or aluminium alloys may not be sufficient to satisfy the design requirements maintaining low production costs. Referring to this, more detailed studies on mechanical and physical properties of CGI as a function of the content and morphology of its microstructural constituents have been carried out [4]. Due to its properties, several automotive manufacturers have therefore evaluated CGI for their petrol and diesel cylinder head applications [5-7].

Despite that, the mechanical behaviour of CGI is not yet as adequately known as those of spheroidal grey iron (SGI) and that fact leaves empty space for further CGI studies.

Cast irons are differentiated by the shape of the graphite particles. As shown in Figure 1, the graphite particles in CGI are randomly oriented and elongated, but they are shorter, thicker with respect to other common families of cast irons. Adding, these particles begin to present rounded edges, up to real spheroidal nodules, distinctive for SGI.

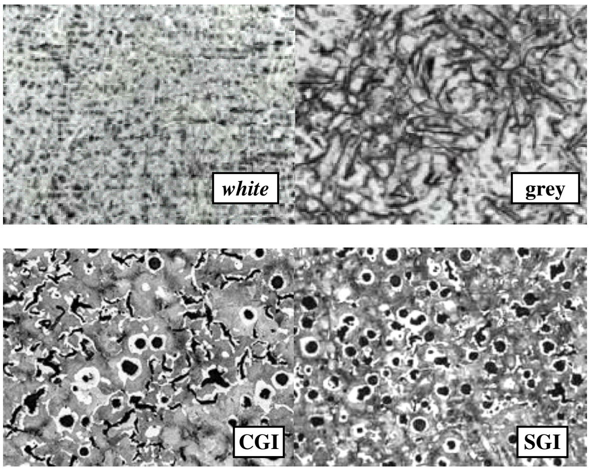

Figure 1. The different microstructures of cast irons. The grade of nodularity progressively increases [1-3].

In contrast to grey and ductile iron (SGI), the entangled compacted graphite 'clusters' interlock themselves into the iron matrix to provide a strong adhesion between the iron and the graphite [8]. The rounded edges of the CGI particles suppress the crack initiation that would otherwise occur at the sharp flake

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edges, while the complex shape of the clusters and the good iron/graphite adhesion impairs crack propagation.

Together, these factors account for the increase in strength relative to grey iron and the improved thermal conductivity relative to ductile iron.

An example of difference in mechanical properties between the cast irons, including CGI, are summarized in Table 1. This comparative table, in line with [9], represents a simplification of information coming from several investigations and represents a valid base for further analysis. It is noteworthy that the final properties for these cast materials strongly depend on the chemical-physical peculiarities of the alloys (as amount of perlite, grade of nodularity, etc.) [10-14].

Referring to the CGI, beyond other traditional studies [as 15-17], two interesting investigations were realized by some of the present authors using similar process conditions and test methodologies. In particular, in [18] a large comparative analysis over the mechanical proprieties of CGI and SGI were realized by tensile tests, permitting to define the Ultimate Tensile Strength, Yield Strength, Maximal Elongation to Failure, Young's Modulus and Hardness.

On the other hand, in [19] several tribological aspects of CGI and SGI were investigated via fracture toughness permitting to relate several proprieties of fracture mechanics to microstructures. During these investigations, standard test methods were used for the determination of fracture toughness (KIC) and plastic-elastic energy (JIC) required to grow a crack in these alloys. It was realized under predominantly linear-elastic, plane–strain conditions using fatigue precracked specimens. Experimental values of KIC and JIC can be used to the design of structures to ensure that a cast does not fail by brittle or ductile fracture. Moreover, in [20, 21] the practical advantages in using CGI, instead SGI are detailed.

The present paper completes the previous analysis proposing an experimental estimation of Poisson’s ratio.

Table 1. Mechanical proprieties of cast irons [9, 18]

Cast Iron	Yield Strenght [MPa]	Tensile Strenght [MPa]	Elongation %	Brinell Hardness
White	140	170	0	450
Grey	280	345	0.5	260
Compacted	365	480	18	170
Ductile	745	930	5	310

2. MATERIAL AND METHODS

2.1 Poisson's ratio measurement

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative.

The definition of Poisson's ratio contains a negative sign, so that normal materials have a positive ratio.

Specifically referring to the scheme in Fig. 2, a cube with sides of length L of an isotropic linearly elastic material subject to tension along the x axis, with a Poisson's ratio of 0.5. The green cube is unstrained, the red is expanded in the x direction by ΔL due to the tension, and contracted in y and z directions by ΔL’.

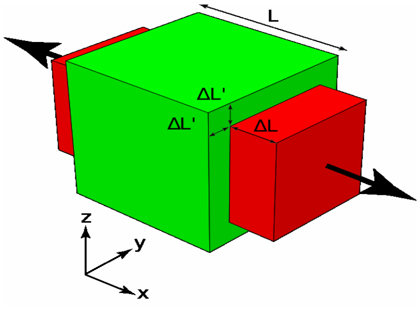

Figure 2. Example of Poisson’s ratio

The Poisson's ratio is defined as:

$$\nu = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}} = -\frac{d\varepsilon_y}{d\varepsilon_x} = -\frac{d\varepsilon_z}{d\varepsilon_x} \qquad (1)$$

where:

$d\varepsilon_{trans}$ is transverse strain (negative for axial tension (stretching), positive for axial compression)

$d\varepsilon_{axial}$ is axial strain (positive for axial tension, negative for axial compression).

Poisson's ratio was evaluated by experimental tensile tests in accordance with a the **EN 10002-1,** using specific “dog-bone” tensile specimens (Fig. 3).

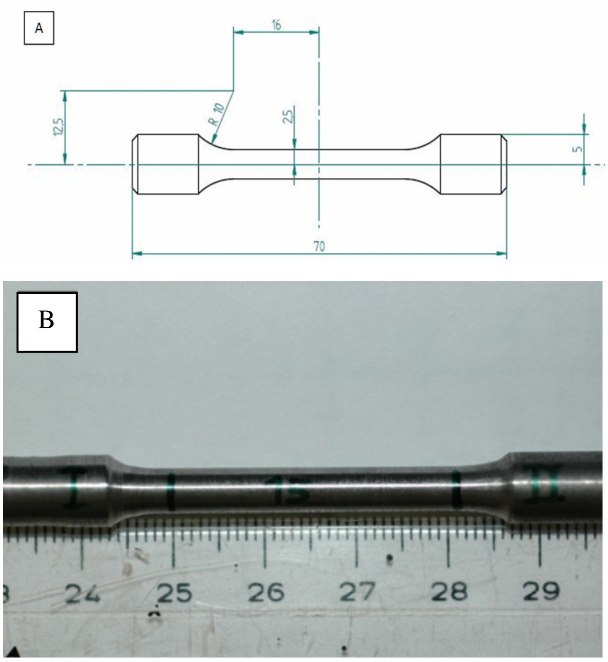

Figure 3: “Dog bone” shaped specimens used for standardized tensile tests: a) geometry; b) final dimension control.

2.2 Specimens design and manufacturing

Tensile tests were carried out on the uniaxial loading tensile testing machine INSTRON® 1343 (in Fig. 4), according to the EN 10002-1 standard where a procedure for the tensile testing of metallic materials at ambient temperature is described [22].

Referring to the tensile specimens, the standardized geometry is reported in Fig. 3A. This shape was machined according to the **EN 1563** standard (Fig. 3B). The EN 1563 is the European standard for spheroidal graphite cast iron. It outlines legal and regulatory requirements as well as industry grades for materials – providing ways to classify the quality and hardness of spheroidal cast irons. Its specifications are based on the mechanical properties of machine tested materials [23].

Figure 4. Servo-hydraulic testing machine INSTRON® 1343

Six specimens were shaped using a CNC tool machine, three in CGI (labelled as *I, II, III)* and three in SGI (labelled as *IV, V, VI*).

2.3 Specimens preparation

Before testing, a strain gauge was mounted on each specimen following a delicate procedure aiming at assuring the perfect match between gauge and surface.

This action started by removing grease and oil on the specimen surface using a solvent (alcohol) and cotton wool. Then, the surface was abraded by silicon-carbide paper (320 grit first) to sand away uneven surface, paint, and rust. It also permitted to smooth the gaging area. Particular attention was reserved to prevent over abrading. Finally, a proper neutralizer provided the right pH level at the specimen surface for better bonding with adhesive.

The strain gauge was bonded on the surface of the specimen applying a film of adhesive; the surface was abraded by sandpaper and finally cleaning by alcohol. Strain gauges were completed by wires connections and specimens ready for cables mounting (Fig. 5).

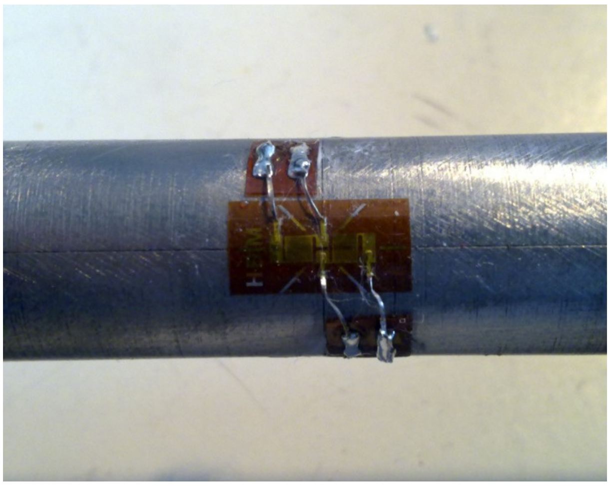

Figure 5. Specimen with strain gauges and wires connection, ready for cables mounting

After the installation on specimens, strain gauges were electrically tested. In particular, the measuring of electrical resistance in condition of open-circuit and close-circuit voltages correctly providing the values of, nearly, respectively, 0 Ω and 120 Ω.

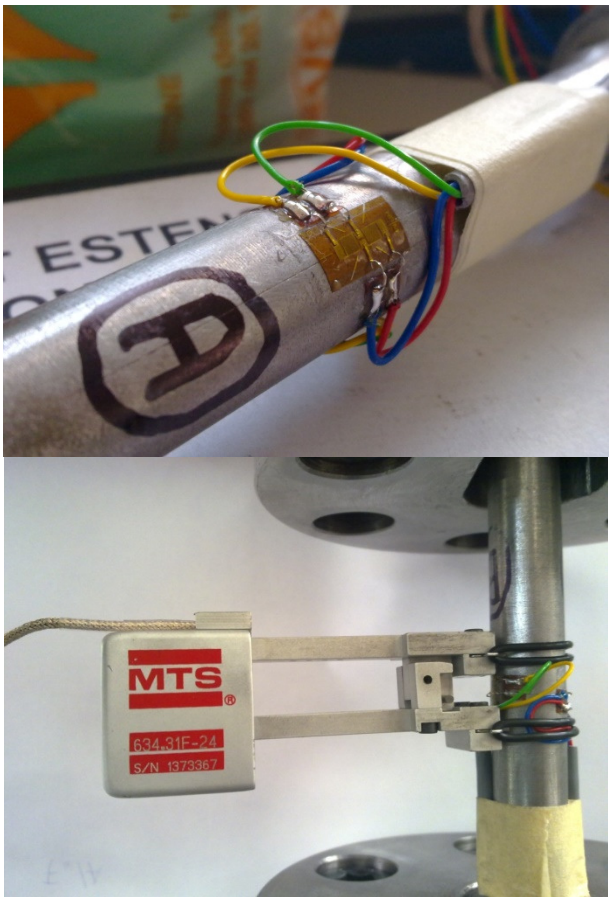

Figure 6. a) Fully prepared specimen ready for Poisson's ratio testing; b) MTS electrical strain converter mounted at tested specimen.

3. RESULTS

Before other considerations, it is noteworthy to report the chemical compositions of castings (Table 2). With the aim at better understanding these values, it is noteworty to recall that specimens were extracted from CGI and SGI green sand castings. Before the pouring, the melt (with a sulphur content lower than *0.01%* wt.) was inoculated by adding ferrosilicon alloys and modified with Fe-Si-Mg master alloys. In the production of CGI castings also Ti was added. In all cases, the pouring temperature was 1400°C.

Table 2. Chemical composition of specimens in cast irons (in % of weight)

	SGI	CGI		SGI	CGI
C	3.66	3.68	Cr	0.062	0.061
Si	2.6	2.67	Cu	0.052	0.05
Mn	0.218	0.215	Mg	0.055	0.014
P	0.032	0.029	Sn	0.013	0.013
S	0.004	0.007	Ti	0.034	0.073
Ni	0.069	0.068	Al	0.011	0.01

Experimental values for stress-strain curves, together with an evaluation of axial strain – transversal strain relation, in the case of CGI and SGI are reported, respectively, in Tables 3 and 4. These data are also compared in Fig. 7 in terms of stress-strain (σ- ε) curves, and in Fig. 8 in terms of axial – transversal strains ($\varepsilon_{axial} - \varepsilon_{transversal}$) distribution.

In particular, graphs show a linear trend. It means that there is a direct proportionality between stress and strain confirming that the experiments remained inside the elastic region for both materials. Furthermore, these trends demonstrated a low variability in experimental data, confirming the possibility to use this procedure for the direct measure of Poisson's Ratio in CGI and SGI.

Table 3. Experimental stress-strain for CGI specimens

Compacted Graphite Iron (CGI)					
I		II		III	
strain [ε]	stress [σ]	strain [ε]	stress [σ]	strain [ε]	stress [σ]
213	31.6	209	31.5	200	31.5
435	64.3	423	64.1	417	64.0
660	96.7	656	96.5	651	96.5
883	128	923	129	918	129

ε_{ax} [%]	ε_{tr} [%]	ε_{ax} [%]	ε_{tr} [%]	ε_{ax} [%]	ε_{tr} [%]
219	535	231	527	232	511
445	1090	470	1060	471	1050
668	1670	708	1620	711	1509
889	2250	945	2290	950	2180

ε_{ax} , ε_{tr} expressed in 10^{-6}

Table 4. Experimental stress-strain for SGI specimens

Spheroidal Graphite Iron (SGI)					
IV		V		VI	
strain [ε]	stress [σ]	strain [ε]	stress [σ]	strain [ε]	stress [σ]
180	31.4	184	31.8	189	31.8
361	63.9	379	65.0	372	64.3
555	97.1	555	96.2	563	96.8
747	130	758	129	758	129

ε_{ax} [%]	ε_{tr} [%]	ε_{ax} [%]	ε_{tr} [%]	ε_{ax} [%]	ε_{tr} [%]
182	462	188	475	186	469
370	921	383	950	376	935
561	1300	567	1400	566	1410
749	1800	759	1800	756	1880

ε_{ax} , ε_{tr} expressed in 10^{-6}

Poisson's Ratio was calculated as individual values (by data experimentally measured for each specimen), as average, medium and standard deviations. These values are reported in Table 4.

Average values for Poisson's ratio can be considered:

ν = 0.226 for Compacted Graphite Iron (CGI)

ν = 0.240 for Spheroidal Graphite Iron (SGI)

Table 4. Poisson's ratio

Compacted Graphite Iron (CGI)		Spheroidal Graphite Iron (SGI)	
specimen:	ν	specimen:	ν
I	0.28	IV	0.23
II	0.23	V	0.24
III	0.16	VI	0.25
average:	0.226	average:	0.241
median:	0.233	median:	0.245
st. dev.	0.061	st. dev.	0.008

These results were in line with the indications of a Poisson's Ratio between 0.21 and 0.26 for cast iron. In two cases regarding CGI, the experimental results were apparently lower (0.16) or higher (0,28) than expected. But after a deeper analysis it was established that all mechanical properties were in the expected range. In particular, experimental data from tests performed over different lots of production, as detailed in [18], permitted to estimate a large variability in material properties in the case of CGI (related to intrinsic factors of processing). This variability is in line with the range of Poisson ratio. Moreover, also the chemical composition and microstructure as reported [19], in appeared in line with the theory. Thus, these extreme values were considered as a statistical divergence.

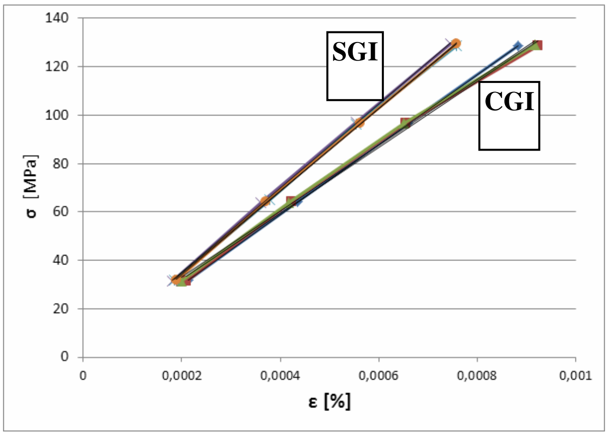

Figure 7. stress-strain curves for CGI and SGI

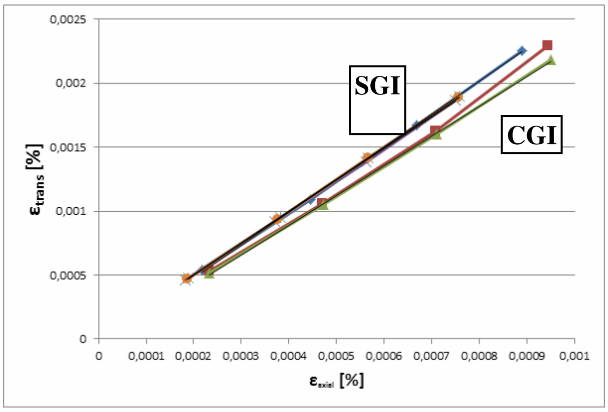

Figure 8. axial strain (εax) vs transversal strain (εtr) curve for CGI and SGI

4. CONCLUSIONS

Poisson's Ratio for Compacted Graphite Iron (CGI) and Spheroidal Graphite Iron (SGI) were measured using tensile tests. The procedure for a direct testing of this mechanical propriety was described in details, including several remarks and suggestions. For both alloys it was possible to verify that Poisson's Ratio is in line with the overall expectations. At the same time, for both of them, it was possible to acquire, also in a comparative way, accurate experimental information as stress-strain curves and intensity of necking effects.

In general, it is important to note that, although SGI is quite largely investigated material in consideration of its wide use for industrial applications and market products, very few studies refers to CGI. A better knowledge on CGI mechanical proprieties, especially regarding proprieties as Poisson's Rate, frequently consider of secondary importance, conversely represents a fundamental step toward CGI formal classification between the other cast irons. Several organizations for standardization are moving in that direction with the aim at promoting its larger utilization in consideration of specific technology advantage offered by CGI respect to other cast irons.

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КОМПАКТНИ И СФЕРИДНИ УГЉЕНИЧНИ ЧЕЛИК: ЕКСПЕРИМЕНТАЛНА ПРОЦЕНА ПОАСОНОВОГ КОЕФИЦИЈЕНТА

К. Фрагаса, А. Павловић

Сфероидни угљенични челик (СГИ), такође познат као нодуларни лив, представља савршен материјал за веома великим опсегом у модерним применама. Успешно се користи где год су потребне оптималне снаге, крутости, па чак и ниски трошкови: високе вредности затезне чврстоће и Young-ов модул су једне од најзначајнијих приметних карактеристика. Истовремено, данас, другачији лив, познат као Компактни Графитни челик (ЦГИ) или вермикуларни графит, тежи да замени СГИ у односу на неке специфичне примене. То зависи од боље ливности, обрадљивости и топлотног отпора. ЦГИ је идеални лив у случају компонената које су истовремено оптерећене механичким и топлотним оптерећењима, као што су цилиндрични блокови и главе мотора.

На жалост, док СГИ има бенефит у широкој научној литератури, ЦГИ је релативно непознат материјал. Поред овога, његова посебна микорструктура, задаје потешкоће у производњи производа од ЦГИ и није лако добити стабилне одговарајуће карактеристике у ЦГИ легури. Овај рад илуструје начин за експерименталну процену Поасоновог односа, коришћењем затезних епрувета, поредећи ову карактеристику у случају СГИ и ЦГИ.