The effects of uniform magnetic field on the mechanical and microstructural properties of concrete incorporating steel fibers

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Abstract

This study investigated the effects of applying a uniform magnetic field (UMF) of flux density 500 mili Tesla (mT) to fresh and hardened concrete specimens with steel fibers at volume ratios of 1 and 1.5% on mechanical and microstructural properties. To attain these objectives, compressive and splitting tensile strengths tests were carried out on the specimens with steel fiber-reinforced concrete (SFRC) at 28 days. Furthermore, the microstructure of SFRC, subjected to the UMF, was assessed via scanning electron microscopy (SEM) images. An electromagnetic instrument, capable of generating a density of 500 mT, was used to produce UMF. Finally, a model equation was proposed to predict the splitting tensile strength of SFRC subjected to the UMF as a function of its compressive strength. The application of UMF to SFRC specimens incorporating 1.5% steel fibers revealed an increase in both compressive and splitting tensile strengths up to about 18.2% and 9.5%, respectively. The SEM analysis indicated that the UMF enhanced the cement hydration process, which is responsible for the higher mechanical strength development of SFRC compared to the control specimen.

Keywords
Magnetic field; Steel fiber-reinforced concrete; Compressive strength; Splitting tensile strength; SEM image.
1. Introduction

Concrete is a brittle material, and in order to compensate its low tensile strength, it needs to make a composite action with steel [1-5]. Incorporating steel fibers into the concrete mixture is an applicable method to enhance the energy dissipation of concrete [6,7]. Following this, steel fibers can have a fundamental role in controlling the propagation of micro-cracks into concrete under tension and thermal stresses by the fiber bridging action [8-10]. This issue can be intensely developed when the steel fibers’ alignment into concrete is in the perpendicular direction to the cracks [11,12]. For this purpose, researchers suggested different methods to align the fibers into concrete materials [13-15]. Among them, electromagnetic fields have been recognized as one of the simple approaches to align steel fibers into concrete and also as a base for producing a new type of orthotropic concretes [16,17]. In addition, magnetic fields can increase the electrical conductivity of concrete due to the arrangement of steel fibers linearly in contact with each other [18,19]. Hence, this is a useful technique for different applications, e.g., electromagnetic shielding and power system grounding [20]. Villar et al. [21] investigated the dynamic behavior of steel fibers in cement mortars subjected to magnetic fields by means of an analytical model based on the Bingham model.

According to the literature, applying a magnetic field to concrete mixing water can enormously improve the workability and mechanical properties of various types of concrete [22-25]. Considering the fact that water molecules can be considered as polar molecules with opposite ends of the molecule with opposite charges, the magnetic field could significantly influence the surface tension and other physical properties of water such as viscosity, temperature, electric conductivity, pH, solubility, specific weight and permeability pressure [26-29]. Gholhaki et al. [30] investigated the effect of the properties of self-compacting concrete (SCC) encompassing magnetic water. The obtained results showed that the magnetic water enhanced the workability and mechanical strength of the concrete up to 8% and 18%, respectively. This resulted in a reduction of water absorption content by 10%. In addition, a reduction of 45% in the superplasticizer content was observed. Furthermore, magnetic field treated water can reduce the amount of cement up to about 5%, and improve the microstructure of concrete by forming more C-S-H gel during the hydration process of cement, see Su et al. [31,32].
According to previous studies, mechanical properties of fresh concrete could be increased by direct applying of a magnetic field [33-40]. In an study by Soto-Bernal et al. [33], it is reported that the compressive strength of cement pastes exposed to weak magnetic fields enhanced up to 13%. In addition, the same results are reported in another experimental investigation conducted by Abavisani et al. [34], where applying a magnetic field to concrete improved its mechanical strength up to about 17%. It is also shown that the magnetizing technique can control the orientation of fibers in the intended direction and make an orthotropic concrete. Following this, the effect of magnetic field on bending capacity of recycled mortar containing steel fibers was conducted by Ferrandez et al. [35]. The results indicated that the magnetic field could increase the bending capacity of mortar by 10%. Recent research revealed that magnetic field could improve the mechanical properties of the hardened concrete specimens as well. Concerning this, Abavisani et al. [36] reported that applying a magnetic field to hardened concrete specimens increased their compressive strength by 8%. It is also shown that the hardened reinforced concrete (RC) beams exposed to a magnetic field, could have a greater bearing capacity of about 7% compared to the reference beam [37]. Furthermore, the experimental investigation conducted by Rezaifar et al. [38] clarified that the compression behavior of hardened RC columns under magnetic field is improved by 11%. Hajforoush et al. [39], in an experimental campaign, studied the mechanical properties of concrete containing steel fibers under a homogeneous magnetic field treatment. However, their study has not investigated the microstructure properties of concrete specimens exposed to the magnetic field using microscopic images. In addition, the effects of magnetic field on concrete specimens with different volume fractions of fibers and splitting tensile strength of concrete have not been addressed. The results indicated that magnetic field could increase the flexural and compressive strengths of concrete by about 16% and 18%, respectively. Besides, the magnetic field led to a decrease in the permeable porosity and water absorption content of concrete by around 18% and 11%, respectively. This resulted in improved durability of concrete in aggressive environments such as coastal and marine.

One of the other advantages of using a magnetic field in the concrete industry is to consolidate fresh concrete mixtures. Xue et al. [41] used the magnetic forces to vibrate cement mortar containing steel
fibers. According to their results, the number of rotated fibers in mortar was greater than the same mortar which is vibrated by means of a shaking table. In addition, Abavisani et al. [36,37] showed that the magnetic fields could be efficiently used for the vibration of concrete. It is explained that the movements created by the magnetic field can be due to the presence of charged particles in sand and cement. The same observation is described by Chen et al. [42]. It can be clearly seen that the research studies on mechanical properties of steel fiber-reinforced concrete (SFRC) specimens exposed to magnetic fields are so limited in the technical literature. To the best of authors’ knowledge, there is no study dealing with the effect of applying a uniform magnetic field (UMF) to fresh and hardened SFRC specimens containing various volume fractions of fibers on the microstructure properties. The present experimental campaign investigated the mechanical properties of SFRC with various volume fractions of steel fibers (1% and 1.5%). As obtained from the previous studies [11,14,21], adding steel fibers at various volume fractions to fresh concrete can significantly affect the alignment of fibers. Thus, it changes the mechanical strength of concrete at the age of 28 days. Meanwhile, Song and Hwang [6] illustrated that the compressive strength of concrete with the volume fractions of 1 and 1.5% has the most increase compared to other fractions. In addition, microstructure of the SFRC subjected to the UMF was evaluated by means of scanning electron microscopy (SEM) imaging. After all, an analytical equation has been offered to predict the splitting tensile strength of SFRC subjected to the UMF in regard to their compressive strengths results. The proposed equation was then compared to those recommended by ACI 318-14 [43] and CEB–FIP [44] for plain concrete. To make UMF, a magnetic instrument capable of causing the intended magnetic flux density was fabricated. In the present study, the magnetic flux density was about 500 mili Tesla (mT), as recommended and used by previous researchers [36-38].

2. Materials and methods

2.1. Materials used

In this experimental campaign, type II Portland cement with a specific surface area of 3200 cm²/g and a density of 3155 kg/m³ was used in accordance with ASTM C150 [45]. Table 1 presents the chemical compositions of the used cement. The fine and coarse aggregates complying with the requirement of
the ASTM C33 [46] were utilized where the density, water absorption, and the maximum size of river sand used for the mix preparation were 2700 kg/m\(^3\), 1.4\%, and 6 mm, respectively. Furthermore, the corresponding values for coarse aggregates (crushed gravel) were 2750 kg/m\(^3\), 0.55\%, and 19 mm, respectively. Table 2 presents the details of aggregates grading in accordance with the requirement of the ASTM C136 [47]. According to the ASTM C494 [48], a superplasticizer based on carboxylate was used in the experiments. Its specific density and pH were equal to 1150 kg/m\(^3\) and 7.05, respectively. As shown in Fig. 1, the ferromagnetic fibers were hooked-end steel fibers with 50 mm length and 0.8 mm diameter. The main characteristics of these fibers are given in Table 3. The number of fibers in the mix design was based on the concrete volume (1\% and 1.5\%).

2.2. Electromagnetic instrument employed in this study

When an electric charge flows through an electromagnetic coil, the magnetic field is perpendicular to the plane of the coil, see Fig. 2. Following this, Fig. 3 illustrates the electromagnetic coil, used in this work, included a loop of wire and a DC power source for producing the intended electric current. The magnitude of the magnetic flux density at the center of an electromagnetic coil is determined by Eq. (1) [49]:

\[
B = \frac{\mu_0 NI}{2R}
\]  

(1)

where B is the magnetic flux density in Tesla (T), \(\mu_0\) is the permeability of free space which has the value of \(4\pi \times 10^{-7}\) T.m/A, N is the number of turns of wire, I is the electric current through the coil in amperes (A), and R is the radius of coil in meters (m).

In the electromagnetic instrument used in this study, the bobbin of the coil with a radius of 100 mm was manufactured using PVC plastic and wound with copper wires of 1.35 mm. The electric current was employed to produce the intended magnetic field with an intensity of 7 amperes, which was produced by means of a 500 volt-ampere power supply. In order to decrease heat in the wires, pressman sheets were used among them. Finally, the magnetic field strength in the coil was measured utilizing a gauss meter where the intensity of 500 mT was obtained from the instrument, as suggested by [34] and [38] for magnetizing concrete mixes.
2.3. Mix design and tests methods

The compressive and splitting tensile strengths tests of SFRC subjected to the UMF were conducted on 100 mm³ cubes and 100 x 200 mm² cylinders at the age of 28 days, respectively. To prevent magnetic leakage, all concrete molds were made up of PVC plastic with a thickness of 6 mm. The average values of five tested specimens were considered as the final value of each test. The SFRC specimens were categorized into four groups: a) control (Ctrl) specimens (with no fiber) which were not exposed to the UMF, b) non-magnetized (Non-M) specimens (with 1% and 1.5% volume fractions of fiber) which were not subjected to the UMF, c) pre-magnetized (Pre-M) specimens (with 1% and 1.5% volume fractions of fiber), which were exposed to UMF until casting concrete into the molds, and d) post-magnetized (Post-M) samples (with 1% and 1.5% volume fractions of fiber), which were subjected to UMF while the hardened concrete samples were examined at an age of 28 days. It is worth noting that the compressive strength test was performed on both Pre-M and Post-M specimens, while the splitting tensile strength test was only carried out on Pre-M specimens. Based on the authors' knowledge, the pre-magnetizing of concrete specimens can significantly improve the tensile strength of SFRC owing to the alignment of fibers in the concrete. Meanwhile, the post-magnetizing of the specimens has an insignificant impact on the mechanical strength of concrete, as reported by Abavisani et al. [36]. Finally, all Pre-M and Post-M specimens were compared to Non-M and Ctrl specimens. Table 4 presents the total characteristics of test specimens. As illustrated in Fig. 4, the Pre-M specimens were exposed to UMF for 2 minutes as recommended by Hajforoush et al. [39]. While the UMF was applied to Post-M samples during the test until collapse. The directions of UMF applied to Pre-M, and Post-M specimens are schematically shown in Fig. 5. Following this, Fig. 6 indicates the compressive strength test procedure on the Post-M specimens. To achieve the objectives of this experimental study, the concrete mixtures were prepared as listed in Table 5. The mix design of SFRC was prepared in relation to the ASTM C192 [50]. In the first step, the coarse and fine aggregates in addition to one-third of the water were introduced into the mixer. In the next step, the remaining mixing water (containing superplasticizer) and cement were added to the mixer. Then, steel fibers were added, in a period of 1-2
minutes, into the mixer. The mixing process was continued for 3 minutes. The concrete specimens were demolded after 24 hours. The specimens were cured under wet conditions until 28 days.

3. Results and discussion

3.1. Compressive strength

The obtained results of the compressive strength of SFRC specimens under the influence of UMF are illustrated in Fig. 7. It was revealed that the application of UMF to both fresh and hardened concrete samples increased their compressive strengths at 28-day. Meanwhile, exposing fresh concrete to the UMF had a more denotative effect on its compressive strength. Despite the fact that the compressive strength of the Non-M specimen depended on its first crack strength, the Pre-M specimen could withstand the compressive load until failure. Following this, the alignment of steel fibers into the concrete mixture was shown to be perpendicular to the crack plane, where they could easily restrain the cracks by fiber bridging action. Hence, the compressive strength of concrete samples enhanced using the UMF. Concerning this, the compressive strengths of Pre-M and Post-M samples with 1% of steel fibers were enhanced by 17.4% and 6.6%, respectively, compared to Non-M sample. These amounts for the Pre-M and Post-M specimens with 1.5% fiber ratio were up to 18.2% and 9.7%, respectively. The obtained results are in acceptable agreement with the results reported by [34,36] for fine aggregate concrete subjected to a magnetic field. The reason is that the effect of magnetic field on concrete induced an increase of the C-S-H gel with a less porous and denser morphology during the process of hydration, leading to a reduction of the porosity value and consequently an increase in the compressive strength of concrete. Furthermore, the orientation of steel fibers in concrete samples subjected to UMF could significantly decrease the propagation of cracks in the concrete under compressive load. For the Pre-M specimen, as the applied UMF was in a perpendicular direction to the applied compressive load, fibers could better restrain the cracking of concrete. This agrees well with the presented results by Safari Tarbozagh et al. [51]. The inclusion of steel fibers at two volume fractions of 1% and 1.5% increased the compressive strength by 16.1% and 30.6%, respectively, compared to the Ctrl specimen. It was shown in Fig. 7 that the increase in steel fiber content resulted in an increase in compressive strength.
Regarding this, the compressive strengths of Pre-M and Post-M specimens increased up to 13.4% and 15.8% by the inclusion of 1% and 1.5% volume fractions of fibers, respectively.

As shown in Fig. 8, there is a significant difference in the failure pattern of SFRC specimens under compressive load in the presence of the UMF. It can be inferred that the compressive strength of the Non-M specimen depended on its first crack strength, where steel fibers could not have a remarkable effect on the compressive strength of concrete. While in the SFRC specimen under the application of UMF, alignment of the fibers was perpendicular to the crack plane where they could strongly restrain the cracks by the fiber bridging action. Hence, steel fibers increased the compressive toughness of concrete and the ultimate crack width. This result agrees well with the reported results by Mudadu et al. [52], where their study evaluated the effect of fiber orientation on the post-cracking behavior of SFRC.

### 3.2. Splitting tensile strength

Fig. 9 illustrates the results of splitting tensile strength of the SFRC specimens containing 1% and 1.5% steel fibers under the application of UMF. The tensile strength of the Pre-M specimen containing 1% volume fraction of steel fiber was increased by 6.5% compared to the Non-M specimen. Furthermore, applying UMF to the fresh specimens with 1.5% steel fibers increased the tensile strength up to about 9.5%. By increasing the temperature of the specimens under UMF, a molecular restructuring process occurred in the specimens led to a reduction in the concrete porosity value. Moreover, the calcium hydroxide content, with the chemical formula Ca(OH)$_2$, was reduced by imposing UMF to the fresh concrete specimens. The UMF could transform the calcium hydroxide into calcium silicate hydrate gel where it is a main reason for the development of compressive and tensile strength of cementitious composites. This resulted in improved bond strength between the steel fiber and hydration products. Therefore, the tensile strength of concrete under the application of UMF was enhanced. This result agrees well with [33] for cement pastes under weak magnetic fields and also by [11] for mortar. Besides, the incorporation of steel fibers with the volume fractions of 1% and 1.5% into concrete increased its tensile strength to 16.4% and 24.9%, respectively. As per Fig. 8, it can be seen that the increasing steel fiber content in concrete led to an increase in its tensile strength. Concerning this, the tensile strength
of Pre-M specimen increased by 10.3% due to the increase in the steel fiber content from 0 to 1.5%.

The general trend for the tensile strength of concrete specimens was similar to what was observed for the compressive strength presented by [26] and also by [30] for SCC with magnetic water.

The correlation between the splitting tensile and compressive strengths of concrete specimens at 28-day age is given in Fig. 10. Following this, the equation of \( f_s = 0.65(f_c)^{0.5} \) has been proposed to calculate the splitting tensile strength of concrete specimens (subjected to UMF) based on their compressive strength where a high correlation coefficient of \( R^2 = 0.94 \) was observed by the fitted curve to the collected experimental data. The results calculated by this equation are very close to values predicted by ACI 318-14 [43] and CEB-FIP [44] for plain concrete. The splitting tensile strength for a plain concrete with no UMF is calculated by Eq. (2) with respect to ACI 318-14 code [43]:

\[
f_s = 0.55(f_c)^{0.5}
\]  

(2)

When the UMF is imposed to the fresh concrete samples, the Eq. (2) can be modified as Eq. (3) as shown below:

\[
f_s = \sqrt{\alpha} 0.55(f_c)^{0.5}
\]  

(3)

Exposing fresh concrete samples to the UMF caused to modify presented \( f_s \) by ACI 318-14 code [43] to \( \sqrt{\alpha} f_s \), where coefficient \( \alpha \) is proposed by 1.4. In this investigation, as suggested by ACI 318-14 [43], the cube compressive strengths of SFRC samples were altered to cylindrical ones \( f_c \).

### 3.3. Scanning electron microscopy (SEM) analysis

The microscopic images correspond to the Non-M and Pre-M specimens are illustrated in Figs. 11(a) and 11(b), respectively. As it is shown in this figure, that there is a major difference in relation to the amount and morphology of the C-S-H gel, which is the main hydration product of cement. The SEM analysis indicated that the UMF enhanced the cement hydration process, responsible for the higher mechanical strength development of SFRC than the control specimen. Applying UMF to fresh concrete provided a complete hydration process than the concrete with no magnetic treatment. The morphology of the gel became denser than the specimens with no UMF. This could be due to a molecular
restructuring process during hydration process of cement, which led to improving the quality of concrete subjected to the UMF. In addition, applying UMF to fresh specimens provided completed cement hydration compared to conventional concrete. The observed result is in good agreement with [33] for cement pastes. As per Fig. 11, using a magnetic field increased the chemical reactions during the cement hydration. The reason might be that the magnetic field created more crystalline phases in crystallization process. The crystals, which shaped in the non-M sample, contained several pores developed among the paste. Exposing fresh SFRC to the UMF reduced calcium hydroxide, which is responsible for the mechanical strength reduction of cementitious composites. Furthermore, the UMF could transform calcium hydroxide into the C-S-H gel during the hydration process of cement. This might be one main reason for the mechanical strength development of concrete under the application of the UMF.

4. Conclusions

In this study, the microstructural and mechanical properties of concrete samples subjected to UMF of 500 mT were evaluated considering the different fiber content (1% and 1.5%). Following this, compressive and splitting tensile strengths tests were conducted on the SFRC specimens under the application of UMF. In addition, the SEM test was employed to assess the microstructure of the samples under UMF exposure.

- Exposing fresh SFRC specimen to UMF (Pre-M specimen) increased its compressive strength at the age of 28 days up to 17.4% and 18.2% at the steel fiber content of 1% and 1.5%, respectively.
- Compressive strength of SFRC specimen subjected to simultaneous compressive load and UMF (Post-M specimen) was enhanced by 6.5% and 9.7% at the steel fiber content of 1% and 1.5%, respectively.
- Applying the UMF to Pre-M specimen with steel fiber volume fractions of 1% and 1.5% increased their splitting tensile strengths at the age of 28 days up to 6.5% and 9.5%, respectively.
A strong correlation exists between the compressive strength and the splitting tensile strength of SFRC under the UMF. The equation of $f_c = 0.65(f_s)^{0.5}$ was proposed to estimate the splitting tensile strength of SFRC specimens exposed to the UMF with an acceptable correlation coefficient of $R^2 = 0.94$.

The SEM images demonstrated that the amount of C-S-H gel becomes more extensive in the presence of the UMF. Furthermore, the morphology of the gel became less porous and denser by applying the UMF. Thus, cement hydration products and their chemical reactions increased by using the UMF.

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**Figure and table captions**

Table 1. Chemical compositions of type II Portland cement.

Table 2. Sieve analysis of aggregates.

Fig. 1. Steel fiber used in the study.

Table 3. Steel fibers characteristics.

Fig. 2. The direction of magnetic flux lines inside a coil.

Fig. 3. The electromagnetic instrument used in the present study.

Table 4. Total characteristics of test specimens.

Table 5. Mix proportion of SFRC specimens.

Fig. 4. Magnetizing of Pre-M specimens for 2 min.

Fig. 5. The schematic of direction of the magnetic field applied to Pre-M and Post-M specimens, (a) the Pre-M specimen subjected to UMF upon casting, (b) the direction of UMF applied to Pre-M specimen and compressive load in a comparison test, (c) the Post-M specimen exposed to simultaneous UMF and compressive load, (d) the direction of UMF applied to Pre-M specimen and compressive load in tensile the test.

Fig. 6. Concrete compressive strength test on the Post-M specimen exposed to the UMF.

Fig. 7. Compressive strength of 100 mm cubes for the SFRC specimens under the application of UMF.

Fig. 8. Two SFRC specimens: (a) Non-M specimen, and (b) Pre-M specimen.

Fig. 9. Splitting tensile strength of 100 × 200 mm cylinders for the SFRC specimens under the application of UMF.

Fig. 10. Variation of the compressive strength vs. splitting tensile strength for the SFRC specimens under the application of UMF.

Fig. 11. Microstructure of SFRC by means of SEM imaging: (a) concrete without magnetic treatment, and (b) concrete with magnetic treatment.
Table 1.

| Item  | Cement (%) |
|-------|------------|
| SiO₂  | 22.45      |
| Al₂O₃ | 4.85       |
| Fe₂O₃ | 3.95       |
| CaO   | 64.86      |
| MgO   | 0.8        |
| SO₃   | 0.85       |
| K₂O   | 0.51       |
| Na₂O  | 0.25       |
| L.O.I | 1.48       |

Table 2.

| Sieve size (mm) | 0.075 | 0.15 | 0.3 | 0.6 | 1.18 | 2.36 | 4.75 | 9.5 | 12.5 | 19 |
|-----------------|-------|------|-----|-----|------|------|------|-----|------|----|
| Fine-aggregate passed (%) | 1.5 | 6.9 | 17.2 | 30.7 | 52.8 | 81 | 95 | 100 | 100 | 100 |
| Coarse-aggregate passed (%) | - | - | - | - | - | 1.7 | 22.39 | 93.26 | 99.9 | 100 |

Table 3.

| Length (mm) | Diameter (mm) | Aspect ratio (l/d) | Young's modulus (GPa) | Tensile strength (MPa) | Ultimate strain (%) | Density (g/cm³) |
|-------------|---------------|-------------------|------------------------|------------------------|---------------------|-----------------|
| 50          | 0.8           | 62.5              | 200                    | 950                    | 4                   | 7.85            |
Fig. 2.

Fig. 3.

Table 4.

| Specimen name | Steel fiber content (%) | UMF (mT) | Performed test (Compression/Tensile) | Number of specimens |
|---------------|-------------------------|----------|--------------------------------------|---------------------|
| Ctrl          | 0                       | 0        | C/T                                  | 10                  |
| Non-M         | 1, 1.5                  | 0        | C/T                                  | 20                  |
| Pre-M         | 1, 1.5                  | 500      | C/T                                  | 20                  |
| Post-M        | 1, 1.5                  | 500      | C                                    | 10                  |
|               |                         |          |                                       | Total=60             |

Table 5.

| Cement (kg/m³) | Water (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Superplasticizer (%) | Steel fiber (%) | Steel fiber (kg/m³) | W/C |
|----------------|---------------|------------------------|--------------------------|----------------------|-----------------|---------------------|-----|
| 450            | 202.5         | 801                    | 890                      | 0.9                  | 4.05            |                     | 0.45|
|                |               |                        |                          | 1.0                  | 78.50           | 117.75              |     |
Fig. 4.

Fig. 5.
Fig. 6.

Fig. 7.

![Graph showing compressive strength (MPa) vs. specimen name. The x-axis represents different specimen names: Ctrl, Non-M 1%, Pre-M 1%, Post-M 1%, Non-M 1.5%, Pre-M 1.5%, and Post-M 1.5%. The y-axis represents compressive strength in MPa, ranging from 0 to 60. The graph compares the compressive strength of different samples.]
Fig. 8.

(a) Not controlled crack
(b) Cracking control by aligned steel fibers

Fig. 9.

| Specimen name | Specimen name |
|---------------|---------------|
| Ctrl          | Non-M 1%      |
| Non-M 1%      | Pre-M 1%      |
| Non-M 1.5%    | Pre-M 1.5%    |

Splitting tensile strength (MPa)
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