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Mechanical behaviour of bio-aggregates based buildings materials

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Abstract

This Technical Letter examines the mechanical behaviour of bio-aggregate building materials (BBM), focusing on their performance under compressive, flexural and shear loading. The study synthesises the findings of various RILEM technical committees and recent research, highlighting the unique properties of BBM compared to conventional concrete. The paper discusses the factors influencing the mechanical behaviour of BBM, including bio-aggregate type, volume fraction, morphology, mineral matrix, mix design, casting process and curing conditions. It presents detailed analyses of the BBM response under different loading conditions, highlighting the different phases observed during testing. The use of Digital Image Correlation (DIC) as an advanced measurement tool to capture BBM deformation is explored, providing insights into the heterogeneity and local behaviour of the material. The importance of the Interface Transition Zone (ITZ) between bio-aggregates and matrix is highlighted, with a focus on its formation and impact on mechanical properties. The paper also outlines the perspectives of a new technical committee aimed at harmonising test procedures and developing scientific data analysis methods for BBM. This comprehensive review provides valuable insights for researchers and practitioners working with bio-based building materials, paving the way for improved understanding and standardisation of the mechanical characterisation of BBM.

Keywords: Bio-aggregates; Mechanical behaviour; Compressive strength; Interface transition zone (ITZ); Digital image correlation (DIC).

1 Introduction

Since 2010, the RILEM scientific community, through its Technical Committees, has been continuously investigating the use of plant-based materials as building materials. The work of TC-236 BBM [1] was dedicated to the characterisation of hemp shiv, which is the most studied in the literature and used, even at industrial scale, to design the BBM. Based on the state-of-the-art report on the physical, chemical, hygrothermal, fire resistance and mechanical properties of hemp shives, a Round Robin Test (RRT) was carried out to define a characterisation protocol taking into account laboratory facilities.

On the basis of the encouraging results of the first committee, a second one, called TC 275-HDB, was set up with two initial objectives: to characterise the hygrothermal behaviour and to study the durability of the BBM. The links between these two objectives are very close, as moisture is one of the main factors for both hygrothermal behaviour and durability. In order to have a better understanding of the current methodology used to assess these properties and also to provide recommendations better adapted to BBM, a comprehensive RRT was carried out by 13 laboratories from 6 countries. As a result of the RRT, protocols were established to characterise the BBM in terms of hydrothermal behaviour and durability [2, 3].

It is worth noting that during the definition of the TC-275 tests, the effect of the compaction direction of the specimens, and consequently the hemp shear orientation during the test, was widely discussed. From this discussion, a third objective was introduced to analyse the effect of hemp shiv orientation on the compressive behaviour of BBM. The experimental results showed a significant variability according to the preferred orientation of the hemp shiv during the test.

The TC MBB: Mechanical behaviour of bio-aggregates based building materials was initiated with the aim of studying the behaviour of BBM under compressive, flexural and shear loading. After an initial literature review based on the compilation of several plant aggregates of different origins used in BBM, it was observed that there was a wide variation in the approaches used by the authors, which made it difficult to make a true comparison between BBM. Consequently, the main objective of the committee will be to unify the way in which the mechanical properties of BBM are measured, as it has been observed that common standards for conventional concrete are not fully applicable.

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2 Mechanical behaviour of BBM

Several factors can influence the mechanical behaviour of vegetal concrete, such as the type of bio-aggregates [4, 5, 6], their volumetric fractions and morphology [4], the type of mineral matrix [8, 9], the mix design [6, 10], the casting process [11, 12], the curing conditions [5], the interfacial transition zone [13, 14], the loading direction and conditions [11, 15].

These key studies have highlighted the significant impact of bio-aggregates on material properties and performance. For instance, Niyigena et al. [4] demonstrated that the characteristics of hemp shiv, such as particle size distribution and water absorption capacity, play a crucial role in determining the properties of hemp concrete. Nguyen et al. [12] further emphasized the importance of compaction, showing that increased compaction enhances both mechanical and thermal performance. Complementing these findings, Arizzi et al. [8] investigated the binder-aggregate interaction, revealing that hemp absorbs much of the water in the lime matrix, resulting in poor adhesion and delayed hardening. Similarly, Diquélou et al. [9] identified binder composition and reactivity as key factors influencing the setting and hardening of hemp concrete. Additionally, Delhomme et al. [13] provided insights into the interfacial transition zone, showing that hemp's extractable components hinder cement hydration, leading to unhydrated regions.

Innovative approaches to mix design and curing have also been explored. Da Gloria et al. [6] proposed a method for optimizing mix proportions in bio-based composites to improve workability and mechanical performance. This was complemented by their work on hybrid designs, where sandwich panels combining wood bio-concrete and sisal fiber composites were shown to have promising potential [7]. On the curing front, Chabannes et al. [16] compared natural and accelerated carbonation curing for rice husk and hemp-based materials, finding that accelerated curing significantly enhances short-term strength, achieving results comparable to 10 months of outdoor natural carbonation. These findings collectively underscore the importance of bio-aggregate characteristics, binder interactions, and advanced design approaches in advancing the performance and application of bio-based construction materials.

The behaviour of the BBM under uniaxial compression, bending and shear loading is presented in this section.

2.1 Compressive behaviour

The uniaxial compression test is one of the most widely used tests for the characterisation of building materials. This test can be performed by monotonic or cyclic loading at constant speed on cylindrical or cubic specimens. Under monotonic loading (Figure 1), the BBMs studied by da Gloria & Toledo [7] present three distinct phases: a linear behaviour (I) up to 30-60% of the maximum stress, followed by a progressive deflection (II) up to the maximum stress. The third phase is characterised by a gradual softening or plateau (III), depending on the volume, morphology, orientation or shape of the bio-aggregates.

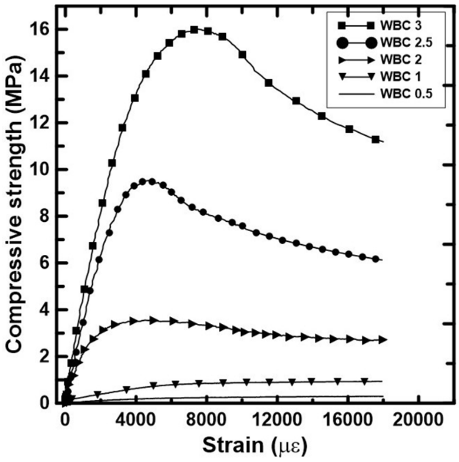


Figure 1. Compressive stress–strain curves of wood concrete [7].

During Phase I, Young's modulus (E) is determined using Hooke's law. At this stage, the mineral matrix is the main source of strength and stiffness. The second stage is characterised by stress propagation around the aggregates and, consequently, progressive cracking of the matrix until the maximum supported stress is reached. In the third stage, softening can be observed following brittle failure of the matrix or permanent plastic strain due to the high deformability of the bio-aggregates.

If the specimen is cubic and produced with a low amount of matrix, a fourth stage, called densification, can be identified. It consists of the densification of the aggregate structure through the compaction of the bio-aggregates, leading to an increase in density, stiffness and load-bearing capacity.

Once subjected to cyclic loading, the compressive behaviour of BBM can be divided into two zones based on the maximum stress: (1) pre-peak zone and (2) post-peak zone [17]. A linear behaviour is observed at the beginning of zone 1, followed by a progressive inflection due to binder cracking up to the peak stress. Residual strains are observed during the loading and unloading cycles. In the post-peak zone, the matrix structure is damaged and the entire load is carried by the bio-aggregates. The higher the volume of aggregates, the lower the stress reduction, despite the higher strain levels. Figure 2 compares the BBM behaviour under both monotonic and cyclic loading and shows the similarity of the curves.

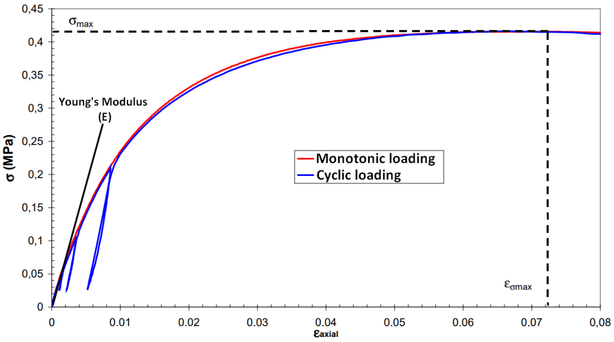


Figure 2. Monotonic and cyclic compression loading curves [17].

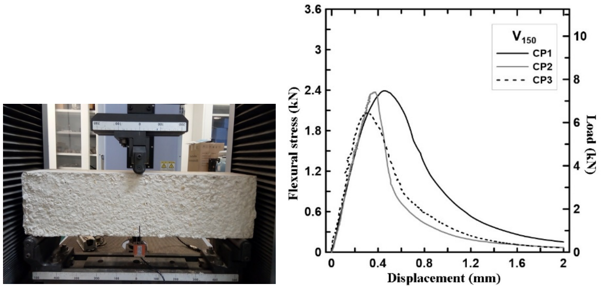
It is worth mentioning that in the interlaboratory comparison of TC HDB 275 [3], the authors observed an increase of the plant-based concrete modulus during the elastic phase. Once the maximum is reached, a decrease of modulus is observed, indicating irreversible damage to the material. The cyclic test specifically allows the evaluation of moduli based on the level of deformation achieved. This is not possible with a monotonic test, which only provides the initial stiffness modulus, which is not truly representative of the maximum stiffness that plant-based concrete can reach.

2.2 Flexural behaviour

The bending test is one of the most frequently performed tests to characterise the BBM. The characteristic values obtained are the modulus of rupture (MOR), which represents the maximum flexural resistance, and the modulus of elasticity (MOE), in accordance with the standards ASTM D1037-12 [18] and EN 310:1993 [19] standards. However, few studies present the load versus deflection curves to analyze the BBM mechanical behaviour.

Da Gloria [20] investigated the behaviour of notched beams made of wood-based concrete under three-point bending test, according to the RILEM TC 162-TDF [21] recommendations. The samples dimensions were 550 × 150 × 150 mm^3 with notch of 2.5 × 25 mm^2 (width × depth) and a span length of 500 mm (Figure 3a).

During the test, three distinct phases are observed as exhibited in Figure 3b: a linear behaviour (I) up to 70-80% of the maximum stress, a progressive deflection (II) up to the maximum stress and a gradual softening (III). The first stage is characterised by a higher stiffness provided by the uncracked mineral matrix. In the second stage, microcracks appear inside the specimen, leading to a progressive reduction in flexural stiffness up to the maximum stress. At this stage, the accumulation of microcracks promotes the formation of a visible and localised macrocrack, which indicates the start of the final stage, characterised by a gradual load decrease. Such decrease can be gradual or abrupt, depending on the test speed, the morphology of the bio-aggregates, their stiffness and the volume fraction.



a) b)

Figure 3. a) Test setup; b) Load vs displacement curves [20].

2.3 Splitting test

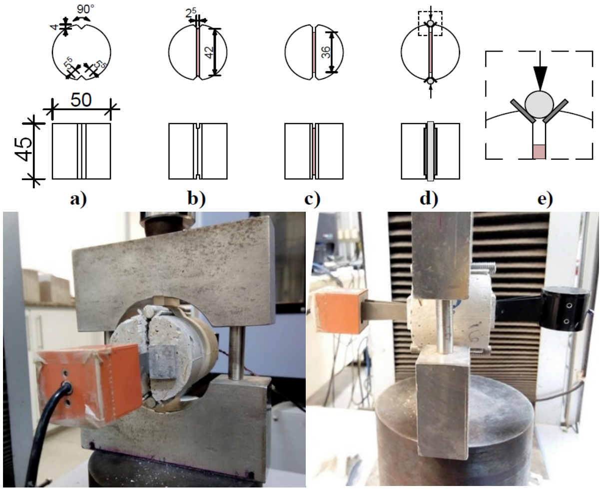
There are very few studies on the behaviour of BBM in direct tensile tests. As with conventional concrete specimens, indirect tensile tests such as the flexure test and the splitting test (Brazilian test) are performed. Silva [22] performed the splitting test (Figure 4a) on cylindrical specimens of BBM made with 45% bamboo particles (by volume). Based on the failure mode observed, crushing of the BBM occurred at the load application areas (Figure 4b), without the separation of the specimens usually observed in conventional concrete.

a) b)

Figure 4. a) Splitting test setup; b) Crushing area of the specimens after the test [22].

The author concluded that the BBM, when subjected to the splitting test, must be studied through configurations that decouple the compressive and tensile stresses. For this reason, following the recommendation of Lameiras [23] and da Gloria [20] carried out the modified splitting test on BBM by introducing notches on specimens of 50 × 45 mm^2 (diameter × thickness) with the aim of inducing a single straight crack.

Three pairs of notches were made. The first pair of V-shaped notches (Figure 5a) with an angle of 90° was made during the production of BBM, since the moulds used have this shape. The second and third pair of notches (Figure 5b) were made using a saw with a depth of 3 mm. The load was applied in the middle of a set of steel rollers and two aluminum plates positioned in the V-notch (Figure 5c). Clip gauges positioned in the center of the specimen (Figure 5d) between two steel plates bonded to the specimen were used to control the crack opening.



f) g)

Figure 5. Modified splitting test setup: a-e) Notches details on the specimen; f-g) Specimen positioned with clip gauge during the test [20].

In the stress-crack mouth opening displacement (CMOD) curves shown in Figure 6, no crack opening was recorded up to 90% of the peak stress. In the post-peak phase, there is an abrupt decrease in stress (about 70%) up to an average crack opening of 0.45 mm. From this CMOD value, a gradual softening of the curve is observed up to the crack opening of 1.5 mm, when the disc showed a complete separation into two parts. The BBM was classified as a quasi-brittle material due to the nature of the fracture.

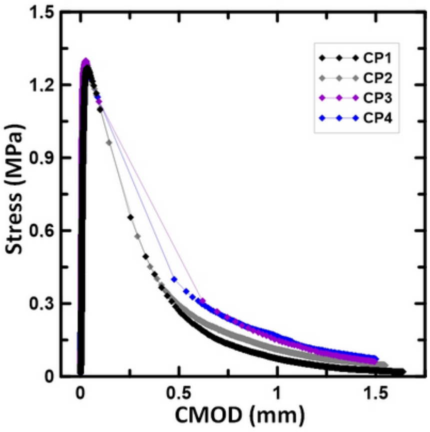


Figure 6. Splitting tensile stress versus crack width of BBM [20].

2.4 Shear test

The modified splitting test (mentioned above) shows the behaviour of the material under Mode I deformation, where the cracks open in a plane perpendicular to the direction of loading. However, Mode II is characterised by crack surfaces sliding without opening in the plane and is analysed by the shear test.

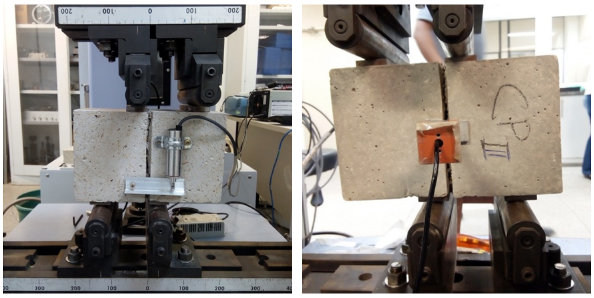
Shear failure is the most common type of component failure, such as wall failure [16]. Therefore, it is fundamental to understand the BBM behaviour under this type of loading. Studies on BBM subjected to shear loading are not widely found in the literature. However, some researchers have performed direct shear tests based on JSCE-SF6 [24] or FIP [25] methods and also triaxial compression test as an indirect shear test. The JSCE-SF6 specifies the method of test by direct double shear while the FIP test is designed to subject the shear plane to pure shear forces, while minimizing the occurrence of a bending moment.

Da Gloria [26] subjected two wood concretes (wood volume of 45 and 80%) to shear based on the JSCE-SF6 standard. The experimental setup and results are shown in Figure 7. The results showed that the BBM with less wood had a higher shear strength but a more fragile failure. This behaviour showed that the shear strength is controlled by the matrix but the post-peak behaviour is controlled by the bio-aggregates. Nevertheless, local crushing was observed at the bottom of the specimen, probably due to the rotation that occurred during sliding.

a) b) c)

Figure 7. Shear test: a) JSCE-SF6 apparatus; b) Specimen cross section after the test; c) Load vs displacement curves [26].

To avoid the crushing observed in the previous setup, the author [20] performed the shear test of wood-based concrete in accordance with the FIP. The test configuration, illustrated in Figure 8, allows shear to occur in the plane bounded by two notches made on opposite sides. A clip gauge and an LVDT were positioned to measure the crack opening in the shear plane and the relative displacement respectively. At the end of the test, no crush was recorded on the specimens.

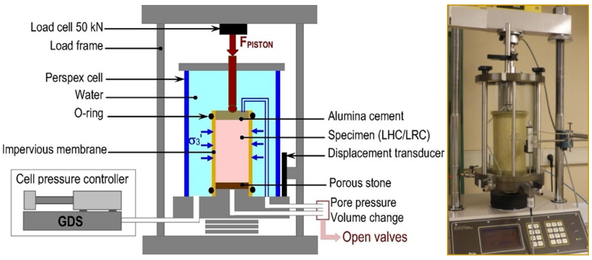


a) b)

Figure 8. FIP Shear test: a) Front side; b) Rear side [20].

The triaxial compression test is also used to access BBM shear parameters. Chabannes et al. [16] evaluate the shear behaviour of two different bio-based concretes under drained conditions at atmospheric pressure. The effective confining pressures applied were 25, 50, 100 and 150 kPa and the schematic representation of the setup is shown in Figure 9a. The final setup of the triaxial shear test is shown in Figure 9b.

From the test results, the authors were able to estimate the peak friction angle and cohesion of the two bio-based concretes, and they also observed a consistent value of cohesion but a different friction angle related to the binder and the aggregate contributions respectively.



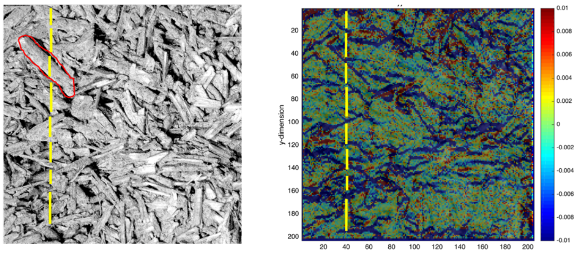
a) b)

Figure 9. Triaxial compression test: a) Schematic representation; (b) Set-up of the BBM [16].

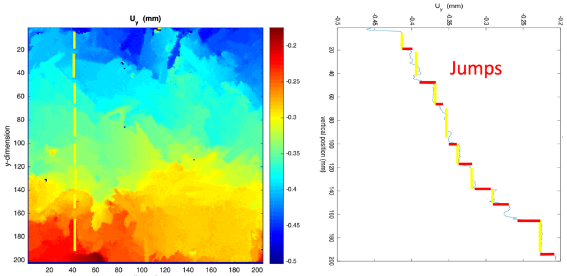
3 Digital image correlation as measurement tool

The mechanical behaviour of BBMs is not described or even presented in some of the literature. This is probably due to two factors: (a) the lack of adequate transducers and acquisition equipment, (b) the difficulty of positioning and maintaining the transducers on the highly deformable BBM specimens during the test. To solve this problem, Digital Image Correlation is an interesting tool to monitor the macroscopic displacements and deformation fields on the specimen surface. Amziane et al [3] subjected hemp concrete to a compression test and monitored the displacements using the DIC technique. For this purpose, they used a PCO 2000 digital camera with a CCD sensor of 2048 × 2048 pixels, coded at 14 bits and equipped with a 105 mm lens, positioned in front of a hemp concrete specimen. The surface was illuminated by a cold light source and the natural texture of the surface provides a random grey level distribution sufficient to calculate the displacements for each correlation pattern. The camera acquisition rate was 0.72 frames/second and the SeptD software was used to process the images and obtain the displacement and deformation fields.

One of the analyses dedicated to the distribution of strain levels between aggregates and binder is presented in Figure 10. While Figure 10a shows the frontal hemp concrete surface, Figure 10b shows a superposition of the previous image with the corresponding vertical strain map. The corresponding vertical displacement map is shown in Figure 10c and the vertical displacement along a yellow dotted line visible in Figures 10a, 10b and 10c is shown in Figure 10d. From Figure 10b it can be seen that the hemp aggregates are slightly deformed and that the deformation is essentially around the aggregates, meaning that it is the binder that is compressed during the mechanical loading. This observation is confirmed in Figure 10d, where the vertical displacement along the yellow dotted line is plotted against the vertical position. Within the aggregates (yellow dashes) the displacement values are the same, meaning that the aggregates are moving but not deforming. Between the aggregates, i.e. in the binder (red dashes), jumps correspond to high displacement values and consequently the deformations are highest in these zones (in accordance with Figure 10b).



a) Hemp concrete b) Strain field



c) Displacement field d) Displacement along a vertical line

Figure 10. a) Image of hemp concrete; b) Superposition with vertical deformations; c) Vertical displacement field; d) Vertical displacement along the yellow line [3].

According to these authors, the use of DIC allows to visualise and understand the heterogeneity of BBM, but also to access local information on the degree of involvement of bio-aggregates in the mechanical behaviour of BBM.

DIC provided the opportunity to isolate a hemp particle and highlight that the deformation is concentrated at the matrix/bio-aggregate interfaces. This indicated that the interface was damaged and negatively affected the contribution of the bio-aggregates.

4 Interface transition zone

The importance of the interface transition zone (ITZ) has been extensively studied by Delhomme et al. [13], as the identification of the size and characteristics of the ITZ is a key parameter to improve the mechanical properties of the BBM. Thus, the authors developed an experimental testing protocol based on image analysis to obtain consistent visual observations of ITZ formation. The protocol consists of 5 steps: (a) grinding 1 g of dry hemp (stored at 50 ◦C) in each of the two compartments of a planetary mill for 2 min and forming 13 mm diameter pellets by compressing 0.1 g of hemp shiv at 100 kN in a manual hydraulic press; (b) preparing the cement paste and pouring it into the 60 × 160 × 35 mm3 mould covered with plastic film; (c) spraying the glue onto the dry pellets and sticking them onto an 8 × 8 cm2 glass plate. Slowly press the glass plate with the glued pellet onto the cement paste, working from one side of the mould to the other; (d) take a photograph every 10 minutes for the first 24 hours, then every hour for up to 3 days; (e) calculate the area of the ITZ by image analysis.

The progressive formation of the ITZ is shown in Figure 11. After their initial contact, the pellet starts to absorb the hydration water of the cement paste. As a result, the area around the pellet becomes drier and after 5 hours the ITZ is visible. The cement paste slowly becomes lighter in the vicinity of the pellet and up to 12 hours the halo appears due to the presence of chemical components that retard or interfere with setting.

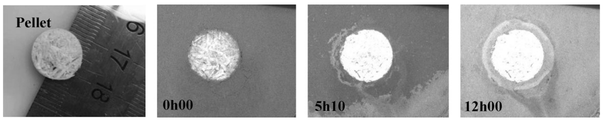


Figure 11. Image acquisition at different times: t = 0 s, t = 5 h10, t = 12 h [13].

From this protocol, the authors were able to conclude (also based on microstructural analyses) that the ITZ is an unhydrated zone of the matrix due to the presence of hemp and its extractable components. A deeper study and understanding of the interfacial transition zone (ITZ) should then be carried out in order to improve the bonding between matrix and bio-aggregates.

5 Concluding perspectives of the new Technical Committee

The mechanical behaviour of bio-aggregate building materials (BBM) is distinct from that of conventional concrete, with compressive, flexural, and shear properties influenced by factors such as the type, volume fraction, and orientation of bio-aggregates, as well as the composition of the mineral matrix and the casting process. The Interface Transition Zone (ITZ) is particularly critical, as it significantly affects the bonding between the matrix and bio-aggregates, emphasizing the need for targeted research to enhance this interaction. Despite advancements such as the use of Digital

Image Correlation (DIC) to analyze local deformation and heterogeneity, the absence of standardized test procedures tailored to BBM poses challenges for establishing reliable comparisons and correlations across studies. Building on the recommendations of previous Technical Committees (236-BBM and 275-HDB), the newly formed MBB Technical Committee aims to address these challenges by harmonising test methods for compressive, flexural, and shear strength through interlaboratory testing. This initiative will not only refine the methodologies for deriving properties like modulus of elasticity and tensile strength but also enable the development of benchmarking tools, scientific data analysis methods, and building codes tailored to BBM. Such efforts are crucial for advancing academic research and fostering the industrial application of bio-based building materials, paving the way for their broader acceptance and implementation in sustainable construction.

Statement

This article has been prepared by the TC chairs of RILEM TC MBB: Mechanical behaviour of bio-aggregates based buildings materials.

Authorship statement (CRediT)

M. Y. R. da Gloria: Conceptualization, Writing – Original Draft, Writing – Review & Editing. **S. Amziane:** Conceptualization, Writing – Original Draft, Writing – Review & Editing.

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