

26 **1. Introduction**

27 Construction demolition waste (CDW) is a worldwide problem. The estimated CDW
28 production in Brazil is higher than 70 Mt/year (around 500 kg/year per capita), but this
29 amount is variable and has correlation with the human development index (HDI). CDW
30 represents the largest amount of municipal solid waste (in mass). The illegally dumped
31 waste in urban areas, nearby creeks, roads and other unprepared places has substantial
32 environmental and economical impacts resulting in financial problems for the community
33 and public administration. In the last years, governments have approved new policies
34 about responsibilities, dumping and recycling of waste in general. As a result, the
35 situation in the major cities is changing with the implantation of recycling plants, but
36 nowadays only a small part of the CDW is recovered.

37 On the other hand, recycling has another environmental and economic advantages, since
38 it reduces the consumption of natural resources. So, there is a comprehensive array of
39 research on the social and financial cost, production, characterization and recycling of
40 this waste [1-4]. CDW recycling plants have been proved to be economically viable [5,6]
41 as well as having a positive environmental impact [7,8].

42 However, it is essential to absorb the output from these plants by the market. In other
43 words, there is a strong need to diversify the industrial applications of this waste. CDW
44 materials have been evaluated and successfully implemented in recent years in several
45 countries [9,10], and generally, it is used as raw mineral materials in paving projects [11-
46 14], footpaths [15] and pipe-bedding [16]. Some author have focused in recycling CDW
47 for concrete production [17-20]. Moreover, others researchers have developed new
48 application as concrete brick [21-22] and concrete block [21,23-25]. Mymrin et al. (2015)
49 have developed a new construction material from CDW and waste from lime production
50 industry with better mechanical properties that Brazilian standards establishes [26]. But

51 there is still a great need for new products, processes and markets, to reduce the volume
52 produced and to recycle most of the CDW [1,3].

53 In general, CDW mineral fraction is very heterogeneous (mortar, ceramics, concrete,
54 rocks, natural gravel, masonry, sand, soil etc.) and depends on the characteristics of each
55 construction. Besides, the extent of economic development of each region defines the
56 chemical composition of the waste [27]. Consequently, CDW presents a wide range of
57 porosity and particles size (bulk specific gravity variability from 1.7 to 3.0 kg/dm³ and
58 water absorption variability from 0 to 20.6%). Essentially, these minerals are mainly
59 made up of silicates from ceramic and natural rocks and carbonates from cement-based
60 particles. Hydrated cement-based phases also must be present. Phyllosilicate content is
61 more relevant in the size fraction below 0.15 mm due probably to soil incorporation [1,4].
62 Although, the CDW fraction below 4.8 mm obtained in most of the plants is, generally,
63 not used and represents approximately 40% of the total mass [2]. The present work is
64 focused and proposes an alternative use for this fraction.

65 In view of the above, the main objective of this work was to evaluate the possibility of
66 producing bricks, using lime or cement as binders, to construct low-cost housing, with
67 construction and demolition waste (CDW) with the fraction below 4.8 mm as substitute
68 of natural aggregates. As secondary objective was to evaluate, in term of mechanical
69 behaviour, the different composition of CDW (mixture 50:20:30 (TSC1) and other
70 randomly obtained in a recycling plant (TSC2)). The physical and technological
71 properties of probes were determined and compared with Brazilian, European and
72 American standards, looking for commercial applications for this residue.

73 **2. Materials and Methods**

74 **2.1 Materials (CDW, Cement and Lime)**

75 Representative samples of two different types of CDW (Class A) [28] were obtained from
76 two different metropolitan regions of São Paulo State (SP) Brazil, in order to compare the
77 heterogeneity of these samples evaluating the technological properties. Sample 1
78 (Presidente Prudente County) was collected from the transporting containers disposed at
79 the work sites of construction and demolition. Sample 2 was collected from a CDW
80 Recycling Plant (São José do Rio Preto County). The samples were grounded and sieved
81 through a 4.8 mm mesh sieve and used only fraction <4.8 mm.

82 According to previous works [29,30], CDW in Presidente Prudente is mainly composed
83 by ceramic (50%), concrete (20%) and mortar (30%). CDW shows a vast array of
84 elements in its composition, majorly containing SiO₂ (40-70 wt.%), CaO (10-25 wt.%),
85 Al₂O₃ (5-20 wt.%), Fe₂O₃ (0.5-8 wt.%) and K₂O (1-4 wt.%). Similar characteristics was
86 also reported in other studies [31-33].

87 Portland cement (type I) and hydrated lime (HL III) were used as binder. Portland cement
88 type I is composed of clinker and gypsum [34]. Portland cement contains mainly CaO,
89 SiO₂, Al₂O₃ and Fe₂O₃ (60-67, 17-25, 3-8 and 0.5-6 wt.%, respectively) as stated by the
90 Brazilian standards (NBR) [35] and the U.S. National Bureau of Standards (NBS) [36].
91 The Hydrated Lime (CH III) is a high quality dolomitic lime, meeting the technical
92 requirements of ABNT 7175 [37]. According to Brazilian building quicklime
93 requirements [38], lime had a CaO and MgO content higher than 88–90 wt.%, and
94 contained appreciable amounts of carbon dioxide (up to 12 wt.%).

95 **2.2 Testing samples (TS) preparation**

96 A total of three series of mixtures were prepared in the laboratory trials as test specimens
97 (TS). Series I and series II mixtures were prepared for producing concrete bricks using
98 CDW from Sample 1 and 2 respectively; series III mixtures were prepared for making

99 lime bricks with CDW Sample 1. The details of these three series of mixes are given in
100 Tables 1. The mix notations indicate the different types of mixes (with TSC for concrete
101 bricks and TSL for lime bricks), the notations of CDW aggregates (Sample 1 and 2), and
102 the percentages (by weight) of the additive (cement or lime) in the total amount. The
103 materials were mixed manually, moistened and homogenized. The cylindrical TS ($\phi = 30$
104 mm, $h \approx 60$ mm), were pressed in triplicate, utilizing a uniaxial manual hydraulic press
105 and load of 7 tonf (tons-force).

106 **2.3 Methods**

107 The particle size analysis of CDW was performed by a mechanical shaker using sieves
108 Granutest model (2.40 mm; 1.00 mm; 0.60 mm; 0.30 mm; 0.15mm and 0.075 mm). The
109 identification of the mineral phases was analysed by the XRD technique (X-ray
110 diffraction) in a Shimadzu diffractometer model XRD 6000, using Cu $\kappa\alpha$ radiation
111 working at 1.2 kW (40 kV e 30 mA). Data were recorded in the 5-60° 2 θ range (step size
112 equal to 1°/minute).

113 Major and trace elements were analysed by Energy Dispersive X-ray Fluorescence
114 (EDXRF) with a Bruker spectrometer S2 Ranger LE equipped with an X-ray tube of 50
115 W (50 kV, 2 mA), anode of Pd, XFlash® Silicon Drift Detector with resolution <135 eV
116 for Mn $K\alpha$ and 100,000 cps, with cooling system type Peltier (without need for liquid
117 nitrogen) and tool changer primary filters with 9 positions available.

118 The behaviour of TS was evaluated on the basis of water absorption (WA), apparent
119 specific mass (ASM) and apparent porosity (AP), according to the Archimedes method.
120 The specimens were dried at a temperature of 110 °C for 24 hours after immersion in a
121 container of water during 24 hours. The TS were weighed dried (dry mass), wet (wet

122 mass) and immersed (mass immersed) using an analytical balance. According to the
123 following equations:

$$124 \quad WA (\%) = \frac{(m_w - m_d)}{m_d} \times 100 \quad (1)$$

$$125 \quad AP (\%) = \frac{(m_w - m_d)}{(m_w - m_i)} \times 100 \quad (2)$$

$$126 \quad ASM (g/cm^3) = \frac{m_d}{(m_w - m_i)} \quad (3)$$

127 Where m_w is the wet mass, m_d is the dry mass and m_i is the mass immersed in water.

128 Compressive strength (σ) was measured using an EMIC apparatus, model DL-2000 on
129 ten test specimens for the three series of TS, with a cell for small test specimen
130 compression.

$$131 \quad \sigma = \frac{F}{S} \quad (4)$$

132 Where F is the applied force (Kgf) on the test specimen and S is the cross section area
133 (cm^2).

134 **3. Results and Discussion**

135 **3.1 Materials Characterization**

136 CDW elemental composition, shown in Table 2, indicates that this waste is mainly
137 composed of Si (71.74 wt.% as SiO_2), Al (14.17 wt.% as Al_2O_3) and Fe (12.11 wt.% as
138 Fe_2O_3). These results are similar to those reported in other previous studies [29-33]. It is
139 also observed a high concentration in other elements as Mg (3.67 wt.% of MgO), Ca (3.44
140 wt.% of CaO), Na (2.86 wt.% of Na_2O) and K (2.68 wt.% of K_2O) according to the
141 mineralogical composition. The trace elements are present at concentrations below 0.1%.
142 The main trace elements identified in the CDW were Ba, Zr, Sr, Zn, V, Cu, Cr, Rb, Pb,
143 Y and As, in order of abundance. Some trace elements (Ba, Sr, V, Cr, Rb and As) are

144 present in concentrations smaller than uncontaminated soils, but others, such as Zr, Zn,
145 V, Cu and Pb are higher [39].

146 The mineralogical composition of the CDW is complex due to the wide range of
147 crystalline and amorphous phases of its components: concrete (coarse gravel or crushed
148 rocks, sand and cement), mortar (sand, lime and cement) and ceramics (fired clay
149 minerals and sand). The RXD analysis confirmed the presence of quartz (SiO_2),
150 carbonates as calcite (CaCO_3), hydroxides (portlandite, $\text{Ca}(\text{OH})_2$) as major crystalline
151 phases and some not identified low intensity peaks, probably due to silicates (Figure 1).
152 These phases are usually present in natural constituents (stone and sand) and in the used
153 additives (cement and lime). These results are in accordance with the data obtained in
154 other works [29,30,40,41].

155 Figure 2 shows the mineralogical composition of some representative test specimens
156 (TSL1-20 and TSL1-30) determined by XRD. The minerals detected included α -quartz
157 (PDF 5-490), calcite and other calcium carbonates (PDF 4-637, CaCO_3 , PDF 47-1743),
158 portlandite (PDF 76-571, $\text{Ca}(\text{OH})_2$) and some peaks not identified are probably associated
159 to silicates. As was expected, the intensity of the quartz peaks decrease with the addition
160 of lime because its concentration decreased. This fact is especially remarkable at 20.8°
161 (2θ). The peaks associated to calcite and portlandite increase with lime concentration,
162 shown principally at 29.7° (2θ). Moreover, the secondary peaks of quartz appear to
163 increase due to the coincidence of peaks of other phases with the quartz or with the
164 preferential orientation of quartz.

165 Furthermore, other phases of carbonates and hydrated calcium silicates are formed during
166 the reaction between CDW and lime or cement mixed with water. These phases as well
167 as the silicates are responsible for increasing the mechanical strength of the material
168 during the curing process. Likewise, carbonates together with organic matter and free iron

169 oxides are other binding agents [42-44]. Calcium carbonate occurs as coating over or
170 between particles binding them, closing pores and improving the technological properties
171 of the testing samples (probes). Besides, the raw materials used to produce red ceramics
172 are rich in iron oxides (hematite e goethite) and clay minerals (kaolinite and mica). The
173 red ceramics used in this region are produced from kaolinitic clays fired at temperatures
174 smaller than 900 °C [45]. The crystalline structures of the clay minerals are destroyed
175 between 500 and 900 °C and transformed in metakaolinite and hematite when the material
176 is fired to produce the bricks (800 to 900°C), releasing the amorphous silica and alumina.
177 The reaction of these amorphous phases to mullite phase formation occurs only at
178 temperatures above 900 °C. Thus, after firing there are iron minerals, fine silica and
179 alumina in the powder of crushed red ceramic materials, and a broad class of siliceous
180 and siliceous aluminous materials can be formed, during the cure process. These
181 materials when finely divided (as is the case of nano-metakaolinite) they have pozzolanic
182 activities and have cementitious (binding) properties. Then, the ceramics materials in the
183 CDW have amorphous phases which will contribute to the formation of new phases
184 together with lime or cement and water contributing to improve the physical properties
185 of the TS.

186 The results of the particle size analysis of CDW are shown in Figure 3. The granulometric
187 profile of CDW revealed that the sample presented a wide range of particles sizes, with
188 an asymmetric distribution of particles, which can be considered as a sandy material
189 (From 2 to 0.075 mm) according to NBR 7225 [46]. Figure 3 denotes two mainly
190 populations of particles. The first population has a significant particle number of around
191 149 µm of diameter. The intermediate fraction is the greatest fraction in this sample; most
192 of the particle distribution in CDW was retained above 1 mm. The mixture of particles

193 with different sizes improves the packing of the particles, decreasing the porosity and
194 water absorption and increasing the TS density.

195 **3.2 Technological properties**

196 The results shown in Table 2 indicate that the apparent porosity decreases with the
197 addition of 20% of cement and increases with the higher cement concentration (30%).
198 TSL has a similar behaviour, the addition of lime up to 25% decreases the apparent
199 porosity and increases with higher lime content (30 and 35%). This physical property is
200 very important, because it is related to the water absorption of the TS [47,8]. Therefore
201 the water absorption also follows this same trend because both properties are directly
202 related, although water absorption is related mostly to open porosity. According to the
203 Brazilian standards [49], the average WA of ceramic components should be at most 22%,
204 for ceramic blocks or at most 18% for roof tiles. Our results in Table 2 agree with this
205 regulations for ceramic blocks (TSC1 and TSC2) and for roof tiles (TSL1). Water
206 absorption should not be greater than 20% by weight according to ASTM C-90 [50] and
207 ASTM C-55 [51] specifications. The maximum water absorption limit is dependent on
208 the weight classification of the brick (light < WA20%; medium < WA15%; normal <
209 WA13%). The result of the water absorption test presented in Table 2 indicates that all
210 the values are agree with the maximum permissible value of 20%. Moreover, the UNE
211 41170 [52] establishes the test method to determine the water absorption and the UNE
212 41166 standard [53] classifies concrete blocks and stablishes the maximum water
213 absorption values: Hllow load-bearing block WA<29%; External non-load Bearing
214 WA<29%; internal non-load bearing WA<32%. Table 2 shows that all TS comply with
215 the maximum values established.

216 The apparent specific mass (ASM) increases with the concentration of cement because
217 its density is higher than CDW and also cement occupy the open pores. On the other hand,
218 with the addition of lime the apparent density presents a wide range of variation.

219 The compression strength (test to calculate the rupture (collapse) of the test specimens,
220 according to equation 4) increases as the binder (cement or lime) percentage increases
221 (Table 2). This result is likely due to the decrease in the volume fraction of
222 interconnecting open pores, which act as large fracture flaws reducing compression
223 strength [54]. Samples composed with 30% of cement did not fracture because the
224 resistance acquired by these TS exceeded the maximum capacity of the load cell utilized
225 (2000 kgf). In relation to the type of fracture obtained in TS after the compression
226 resistance, these shown a prismatic fracture, which is characteristic of TS that are exposed
227 to a homogeneous distribution of load during the test (Figure 4).

228 According to NBR 7170 [55], for ceramic bricks, the axial resistance of massive sintered
229 bricks is classified in the following way: class A < 2.5 MPa; class B $2.5 < 4.0$ MPa; class
230 C > 4.0 MPa. Comparing these data with the values in Table 2, all probes can be classified
231 as Class C. Furthermore, the compressive strength required for load-bearing and non-
232 load-bearing walls using concrete blocks were 6.86 and 3.43 MPa respectively, in
233 accordance with ASTM C-90 [50]. Moreover, the UNE 41166 standard [53] that classifies
234 concrete blocks, designates and establishes the requirements, as well as, the
235 complementing 41167 and 41172 UNE standards [56,57], establish the following values
236 in each type of block: Hllow load-bearing block > 6 MPa; External non-load Bearing > 4
237 MPa; internal non-load bearing > 2.5 MPa.

238 It was observed that the mean values of simple compression strength in TSC with 28 days
239 of curing were very different for the mixtures TSC-10 and TSC-20, showing resistance
240 around 4 and 8 MPa, respectively. According to TSL1 compression strength results,

241 shown similar mean values for the different mixtures, between 5.31-5.65 MPa, obtained
242 the best result in sample TSL1-30. Since there are no particular specifications for bricks
243 with waste added, the results obtained were compared with the limit values for soil-
244 cement bricks and ceramic bricks. The NBR-8491 guidelines [58] state that the mean
245 resistance of soil-cement bricks should be equal to or over 2.0 MPa and that the individual
246 values of the pieces tested cannot be less than 1.7 MPa. Besides, the obtained values were
247 all over the lower limit of 4 MPa for Class C massive ceramic bricks for masonry [55].
248 Additionally, according to the ASTM C-90 and the UNE 41166 standards [50,53], the
249 compressive strength required for load-bearing are 6.86 and 6 MPa, respectively and in
250 case of non-load-bearing walls using concrete blocks are 3.43 and 4 MPa, respectively.
251 The obtained values were all over the both limits established for non-load-bearing walls.
252 In case of TSC-20 and TSC-30, the values obtained was over the lower limit required for
253 load-bearing.

254 On the other hand, the values obtained in the different composition of TSC1 and TSC2
255 were very similar, indicating that the mixture of 50:20:30 (TSC1) for waste is a good
256 approximation in term of mechanical behaviour of TSC2 prepared with CDW obtained
257 randomly in a recycling plant. Despite the heterogeneity of CDW depending on its origin,
258 the products have reached very similar technological properties. Consequently, it was
259 proved that this heterogeneity is not a limiting factor, when CDW is formed majority by
260 ceramic, concrete and mortar

261

262 When compared both limit values, water absorption and compression strength, according
263 to Brazilian standards for ceramic block for masonry ($WA \leq 25\%$ and $\sigma \geq 2.5$ MPa) [59],
264 and the apparent density, for ceramic massive bricks ($ASM > 1.7$ g·cm³), the results are
265 outstanding, all of the values obtained were within the limits. Mechanical resistance to

266 compression was also very good, where all the probes showed values of resistance to
267 simple compression greater than 4.12 and 5.31 MPa in TSC and TSL respectively, both
268 cases can be classified as class C block (limit value $\sigma > 4$ MPa) [30]. All of the values
269 obtained were within the limits established in the UNE 41166 standard ($WA \leq 29\%$ and σ
270 ≥ 2.5 MPa)[53] and the ASTM C-90 standards ($WA \leq 20\%$ and $\sigma \geq 3.43$ MPa)[50].
271 Another option for the construction of low-cost housing, employed in Brazil since 1948,
272 is the one that uses soil-cement [30]. It is widely used in rural areas and in poorer regions
273 due to the technical and economic advantages that the material offers. The Brazilian
274 standards established for soil-cement bricks dictate the following mean limit values:
275 resistance strength ≥ 2.0 MPa and water absorption $\leq 20\%$, after seven days curing
276 [41,60]. Therefore, the values obtained for the TS manufactured with construction and
277 demolition waste and binder additives (cement or lime) are also better than the limit
278 values established for soil-cement bricks.

279 The predominance of silicates and carbonates, the presence of minerals originating also
280 from burning at low temperature (in general < 900 °C) of clays in the structural ceramics
281 and the high concentration of the fine granulometric fraction, favours the lime and cement
282 reaction, which increases the pH of the material, with the residue forming cementing
283 agents (calcium carbonates and silicates) and improving the physical properties of the TS
284 [61]. Therefore, the use of CDW with lime or cement for the production of bricks with
285 appropriate physical properties is a good option for the use of both the fine fractions
286 present in these residues and the more roughly ground fraction.

287 **3.3. Economic and environmental implications**

288 The best result was exhibited by composition TSC-30; however, from an economic point
289 of view, perhaps it would be possible to choose compositions TSC-10 or TSC-20 and
290 TSL1-20 and TSL1-25 to produce bricks. This consideration is founded on the small

291 difference in strength between the samples and, particularly when compared with the
292 requirements of the limits values. In a economic view, lime as binder can be obtained
293 from some of the nearby industries that produce lime as waste, thus avoiding the costs
294 produced by the use of cement.

295 On the other hand, CDW is generated in all the cities and therefore it is available in all
296 places where take place construction and demolition works. Consequently, the cost of
297 transporting will be even lower than those produced by the use of natural aggregates,
298 since these are extracted in quarries that are usually located away from the cities. Besides,
299 the use of this residue as substitute of natural aggregates would reduce the cost of
300 purchase raw materials.

301 Additionally, countries as Brazil which present shortages of natural aggregates, using this
302 waste represents savings cost due to the price of raw material and a solution to this
303 problem of availability. In addition to the environmental benefits in reducing the demand
304 on land for disposing the waste, the recycling of CDW can also help to conserve natural
305 resources and to reduce the cost of waste treatment prior to disposal. Moreover, reducing
306 the polluted areas likewise reduce the spread of disease vectors animals (such as flies,
307 cockroaches, scorpions, rats etc.) attracted by the garbage disposed with the CDW.
308 Another economical result of this action, the city administration will save money spent
309 on cleaning areas with CDW disposed and in health care, with treatment of the affected
310 population.

311 **4. CONCLUSIONS**

312 (a) The present experimental work confirms the possibility of using residues from civil
313 construction (CDW) and binding agents (cement and lime) as raw materials in the
314 manufacture of new construction material as low-cost bricks for masonry walls.

315 Especially, the samples TSC2-20/30 and TSL1-30/70 present the best technological
316 properties. Moreover, the highest values were obtained with cement as binder.

317 (b) According to the technological properties, all the proposed compositions show higher
318 compressive strength values than Brazilian, European and American standards. The main
319 values were 5.47 and 7.61 MPa adding lime and cement respectively. These both are in
320 accordance with the requirements for NBR 7170 in the C Category (minimal compression
321 strength of 4 MPa). ASTM C-90 and the UNE 41166 standards, the compressive strength
322 required for load-bearing are 6.86 and 6 MPa, respectively and in case of non-load-
323 bearing walls using concrete blocks are 3.43 and 4 MPa, respectively. The obtained values
324 were all over the both limits established for non-load-bearing walls. In case of TSC-20 and
325 TSC-30, the values obtained was over the lower limit required for load-bearing.

326 (c) The fraction of CDW with a particle size below 4.8 mm, which is used in this research
327 work and generally rejected in most of the recycling plants, was confirmed as possible
328 substitute of natural aggregated.

329 (d) The initial hydration become lime (CaO) predominantly into portlandite (Ca(OH)_2)
330 and calcite (CaCO_3) according to XRD analyses. These new minerals together with some
331 hydrated silicates may explain the improving in mechanical resistance.

332 (e) The typical used CDW composition (50% ceramic, 20% concrete and 30% mortar), is
333 a good proportion as raw material to produce bricks with better mechanical properties
334 that are established by standards.

335 (f) Similar values of compression resistance in TSC prepared with different samples of
336 CDW (TS1 and TS2), show that the composition of the CDW influences little the
337 mechanical resistance of the TS. This result assures, in principle, that the method can be
338 employed in different recycling units, since it guarantees that the material used is only

339 the mineral fraction contained in civil construction and demolition waste. Furthermore,
340 the present work has shown that construction and demolition waste from different places,
341 with a differentiated composition between them depending on its origin, have achieved
342 the standards according to the technological properties.

343 (g) In a realistic and economical approximation the use of industrial waste as raw
344 materials would reduce the price of civil construction. A sustainable and environmentally
345 procedure directed to manage the CDW will withdraw the huge volume of this waste
346 discarded in the environment or in landfills and will result in a number of important social
347 and environmental impacts: built low-cost houses; to reduce the raw materials utilization
348 increasing the lifetime of the existing mineral deposits; increase the lifetime of the
349 landfill; protect areas of environmental preservation in the cities neighbourhood; reduce
350 the spread of disease vectors animals (such as flies, cockroaches, scorpions, rats etc.)
351 attracted by the garbage disposed with the CDW in the periphery of cities where the
352 poorest people live. As a result of this action, the city administration will save money
353 spent on cleaning areas with CDW disposed and in health care, with treatment of the
354 affected population.

355

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530

531 **Figure captions:**

532 **Figure 1.** XRD patterns of CDW.

533 **Figure 2.** XRD patterns of TSL1 80-20 and TSL1 70-30.

534 **Figure 3.** Granulometric range curve of the CDW.

535 **Figure 4.** Image of the TS before (left) and after compression test exhibiting prismatic
536 fracture (right).

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538

539 **Table captions:**

540 **Table 1.** Composition of the different tests.

541 **Table 2.** Average concentrations (n = 10) of major elements (wt. %) and trace elements
542 (mg kg⁻¹). Major and trace elements measured by EDXRF.

543 **Table 3.** Technological properties for each composition (after 28 days cure).