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The use of wood ash as a supplementary cementing material (SCM) to mitigate the alkali-aggregate reaction (AAR) in concrete

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Abstract

Alkali-aggregate reaction (AAR) is one of the most harmful distress mechanisms affecting the serviceability and durability of concrete infrastructure worldwide. Over the past decades, several approaches and recommendations, including a variety of accelerated laboratory test procedures, have been developed to assess the potential reactivity of aggregates in the laboratory as well as the efficiency of preventive measures (e.g. supplementary cementing materials- SCMs) to mitigate AAR in the field. It has been found that AAR-induced expansion & damage may be prevented by the appropriate use of SCMs. However, the anticipated depletion in the coming years of some of the most common SCMs used in concrete makes imperative the finding of new potential SCMs sources. This research aims to study the use of wood ash (WA), a by-product of biochar combustion, to suppress AAR physicochemical development. Two reactive aggregates and different PC replacement levels by WA (i.e. 10%, 20% and 50% by wt%) are selected for this research. Accelerated tests are performed in the laboratory (i.e. concrete prism test – CPT and the accelerated mortar bar test – AMBT) and comparison and discussion amongst the distinct results obtained are conducted. Recommendations on the use of WA to mitigate AAR-induced expansion and damage will be then provided.

***Keywords**: alkali-aggregate reaction; durability of concrete; supplementary cementitious materials; wood ash*

1. INTRODUCTION

Alkali-aggregate reaction (AAR) is one of the main processes affecting the durability and serviceability of concrete structures in Canada and around the world [1,2]. AAR is composed of two distinct mechanisms: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is by far the most common type of reaction found around the globe; it consists of a chemical reaction between “unstable” silica mineral forms within fine and/or coarse aggregate materials and the alkali hydroxides (Na, K – OH) that are dissolved within the concrete pore solution [3–5]. It generates a secondary product, the so-called alkali-silica gel, that induces expansive pressure within the reacting aggregate material and adjacent cement paste upon moisture uptake, leading to microcracking, loss of material’s integrity and functionality of the affected structure [3–6].

Over the past decades, several approaches and recommendations, including a variety of accelerated laboratory test procedures, have been developed to assess the potential reactivity of aggregates in the laboratory as well as the efficiency of preventive measures (e.g. the use of supplementary cementing materials- SCMs - such as fly ash, silica fume, blast furnace slag, natural pozzolans, etc.) to mitigate AAR in the field [3,7–15]. It has been found that AAR-induced expansion and distress may be prevented by the appropriate use of SCMs [5,7,15]. However, the anticipated depletion in the coming years of some of the most common SCMs used in concrete (e.g. fly ash) makes imperative the finding of new potential SCMs sources able to improve the durability of concrete against AAR [3,7]. Recent studies show that the utilisation of pozzolanic materials from biomass can be feasible to be used as SCMs in concrete and thus partially replace Portland cement (PC) [16–18].

2. BACKGROUND

Wood ash (WA), a by-product of biochar combustion, is being seen as a viable alternative to be used as an SCM in concrete towards a greener and more durable future of the civil industry [17,18]. Wood is a potential source of energy along with an environmentally friendly material; thus, it is anticipated that a significant increased in wood usage for energy production will take place in the future [19,20]. Therefore, the amount of WA generated is also expected to grow, which raises concerns regarding disposal. WA is frequently used as a soil supplement to improve its alkalinity for agriculture purposes. Yet, the vast majority of WA currently produced is disposed in landfills [19,20].

The incorporation of WA as a partial replacement of cementitious materials, specifically PC can be beneficial from both the environmental and economic point of views; giving solution to the waste management problems while decreasing the concrete carbon footprint made entirely of PC. Wood ash is chemically comprised of silica (4-40%), carbon (5–30%), calcium (7–33%), potassium (3–4%), magnesium (1–2%), manganese (0.3–1.3%), phosphorus (0.3–1.4%) and sodium (0.2–0.5%) [17,20]. Its fineness can be compared to PC (i.e. maybe slightly finer, with 50% of the material passing sieve #200 -75 μm, and 30 % retained on sieve #325 - 45 μm), although it is much lighter than PC with a specific gravity of about 2.48 [17,20].

Etiegni and Campbell [21] investigated the chemical and physical properties of WA and promising results were obtained; the authors concluded that the combustion temperature significantly affected the total yield of ash along with its chemical composition. Moreover, wood ash was found to hydrate and thus forming new chemical compounds such as C-S-H and portlandite [21]. Other studies were also conducted on the topic and demonstrated the feasibility of using wood waste ash as a partial replacement of PC in concrete. Results showed that WA might be suitably used as a constituent material for production of structural grade concrete with acceptable mechanical and durability-related properties [22]. These findings displayed a potential solution for WA waste management issues, contributing towards minimizing the energy consumption of high embodied energy PC mixtures. Hence, the incorporation of WA in concrete would be beneficial not only for decreasing the carbon footprint of concrete but rather to reduce costs associated to clinker production [23,24]. Yet, very few data have been reported on the fresh and long-term durability properties of concrete incorporating WA. Furthermore, WA was found to display an extremely variable chemical composition and its behaviour in concrete was verified to be directly linked to its manufacturing process [17,18,20], especially to the heat treatment temperature, hydrodynamics of the furnace and the trees species. The latter emphasizes the importance of a thorough characterization of the ash material prior using in concrete [16,17,20,22,24]. Due to WA chemical composition (i.e. high levels of silica, possibility of having low amount of calcium and alkalis) and depending on its manufacturing process and derived tree species, it may be seen a potential alternative to mitigate alkali-aggregate reaction (AAR)-induced expansion and damage [23].

3. SCOPE OF WORK

As stated above, several techniques and SCMs have been used in the past aiming to assess and mitigate ASR-induced development in the field. However, it is anticipated that the current SCM sources will be depleted soon and thus alternatives are required. Past studies have identified the potential benefits of using WA in concrete; however, very few data have been reported on the fresh and long-term durability properties of concrete incorporating WA. The proposed research focus on the use of WA as a PC partial replacement to mitigate ASR-induced expansion in concrete. Mortar and concrete specimens incorporating two highly reactive aggregates (i.e. Springhill coarse aggregate and Texas sand), and distinct WA amounts (i.e. 10%, 20%, 50% and 60% PC replacement, by mass) are fabricated and stored under controlled environmental conditions enabling ASR development. At selected exposure periods, microscopic (i.e. Damage Rating Index) and mechanical (i.e. Stiffness Damage Test, modulus of elasticity and compressive strength) analysis are conducted and a comprehensive evaluation of WA suitability for mitigating ASR-induced expansion and damage will be performed and discussed.

4. MATERIALS AND METHODS

4.1 Materials and mixture proportions

Accelerated mortar bar (AMBT) and accelerated concrete prism (ACPT) tests were conducted incorporating two highly reactive coarse and fine aggregates as described in Table 4.1. Table 4.2

provides information on the chemical composition of the different binder materials used in this research; i.e. PC-GU type (equivalent to ASTM type I) and WA. As showed in Table 4.2 and differently from expected, the chemical analyses provided by X-Ray Fluorescent (XRF) indicate high amount of CaO and low presence of SiO_2 and Al_2O_3 for the WA selected for this research; the latter indicates that WA should only be effective to mitigate ASR while the use of high replacement ratios. Yet, it was decided (as a first trial basis) to assess the performance of the material anyway.

Table 4.1: Reactive (R) and non-reactive (NR) aggregates used in the research.

Aggregate		Reactivity	Rock Type	Specific gravity	Absorption (%)
Coarse	NC	NR	High-purity fine-grained limestone	2.79	0.42
	SPH	R	Crushed Greywacke	2.73	0.71
Fine	NF	NR	Natural derived from granite	2.67	0.82
	Tx	R	Polymictic sand (granitic, mixed volcanic, quartzite, chert, quartz)	2.63	0.91

[a] Results at 14 days of curing of the accelerated mortar bar testing (ASTM C 1260) carried out on the aggregates selected.

Table 4.2: Chemical composition in mass (%) of the cement and wood ash.

	Cement (%)	Wood Ash (%)
CaO	61.93	48.97
SiO_2	20.1	6.51
Al_2O_3	5.02	0.92
Fe_2O_3	3.79	1.47
MgO	2.42	4.75
K_2O	0.92	8.85
Na_2O	0.3	0.25
P_2O_5	-	2.12
MnO	-	2.05
SO_3	3.37	-
LOI	2.91	23.18
$Na_2O_{eq.}$	1.01	6.06

The current research was divided into two phases. In the first phase, the expansion behaviour of eight different mortar mixtures, incorporating the two distinct reactive aggregate types displayed in Table 4.1 and four different PC replacement levels (i.e. 0%, 10%, 20% and 50%, by mass (wt%)) were evaluated through the AMBT as per ASTM C 1260/1567 (Table 4.3); the results obtained through this phase were taken as a first screening for the second research phase.

Table 4.3: Mortar mixtures with the two different reactive aggregates, according to ASTM C 1260.

Group ID	Fine materials (g)		Water (g)	Fine Aggregates
	Cement	Wood Ash		
Control	440	-	206.8	990g of Tx or SPH aggregates
WA10	396	44		
WA20	352	88		
WA50	220	220		

In the second phase, seventy-two 35 MPa concrete cylinders, 100 by 200mm in size, were fabricated and appraised as per ASTM C1293 (Table 4.4); however, the temperature used in the test was 60ºC (instead of 38ºC) to further accelerate ASR-induced development. Six concrete mixtures, using the two reactive aggregates displayed in Table 4.1, and combining them with non-reactive aggregates and different amounts of PC replacement by wood ash (i.e. 0%, 20% and 60%, by mass (wt%)) were proportioned. It is worth noting that the water-to-binder ratio was kept constant for all mixes.

Table 4.4: Concrete mixtures cast with different aggregates using the same volumetric amount of reactive aggregates.

Mixture	Water-to-fines = 0.45			Aggregates (kg/m^3)			
	Water (kg/m^3)	Cement (kg/m^3)	Wood Ash (kg/m^3)	NF	Tx	NC	SPH
WS-C	189	420	-	836	-	-	938
WS-20		336	84	803	-	-	938
WS-60		168	252	738	-	-	938
WT-C		420	-	-	765	1020	-
WT-20		336	84	-	765	986	-
WT-60		168	252	-	765	917	-

The specimens were demoulded after 24 h of casting. Small holes, 5mm in diameter by 15mm long, were drilled at both flat ends of the samples. Then, studs were glued in place, with a fast-setting cement slurry in order to measure the longitudinal expansions; the specimens were thus moist cured for over 24 h. After 48 h from casting, the “zero” reading was recorded, and the cylinders were placed in sealed buckets lined with a damp cloth and stored at 60℃ and 100% RH. Every 15 days, the buckets were removed from the chamber 16 ± 4 h prior to the samples reading.

4.2 Test methods

Three concrete cylinders from each concrete mixture were selected every thirty days, to perform the following test procedures.

4.2.1 Stiffness Damage Test (SDT)

Concrete specimens were subjected to five cycles of loading/unloading at a controlled loading rate of 0.10 MPa/s. The SDT procedure was performed as per Sanchez et al. [6,25,26], i.e. using a loading level corresponding to 40% of the 28-day compressive strength. To characterize all mixtures at 28 days, samples were wrapped and placed at 12°C, since some of the specimens contained highly reactive aggregates and ASTM C 39 method could not be followed as they could develop some ASR. The cylinders were maintained at 12°C for a 47-day period, according to the maturity concept as by ASTM C 1074.

4.2.2 Damage Rating Index (DRI)

A semi-quantitative petrographic analysis, using the DRI was performed on one specimen from each concrete mixture as per Sanchez [6,27]. The DRI final number presented hereafter is the normalized 100 cm^2 value obtained over polished concrete specimens.

4.2.3 Compressive Strength Test

Compressive strength was conducted on the samples with two different and specific goals. First, as previously mentioned, the 28 days compressive strength of each mixture was obtained considering the maturity concept as by ASTM C 107 to obtain the ultimate capacity of the mixtures designed. The second compressive strength measurements were carried out on three cylinders used for stiffness damage testing, with the aim of verifying the compressive strength loss of the material as a function of ASR development. This procedure was adopted and considered valid after Sanchez et al. [6,27] confirmed the non-destructive character of the SDT.

5. RESULTS

5.1 ASR kinetics

In this section, ASR expansion kinetics and amplitude results are presented for all 8 mortar bar mixtures and 6 concrete mixes fabricated in the laboratory. Figure 5.1 displays the results obtained through the Accelerated Mortar Bar Test (AMBT), in which Figure 5.1a shows data from mixtures made of Tx sand while Figure 5.1b presents the results of mixtures incorporating the crushed SPH. In general, the mixtures containing Tx presented faster reactivity than those incorporating SPH. Moreover, for both aggregate types, the higher the PC replacement by WA, the lower the expansion reached.

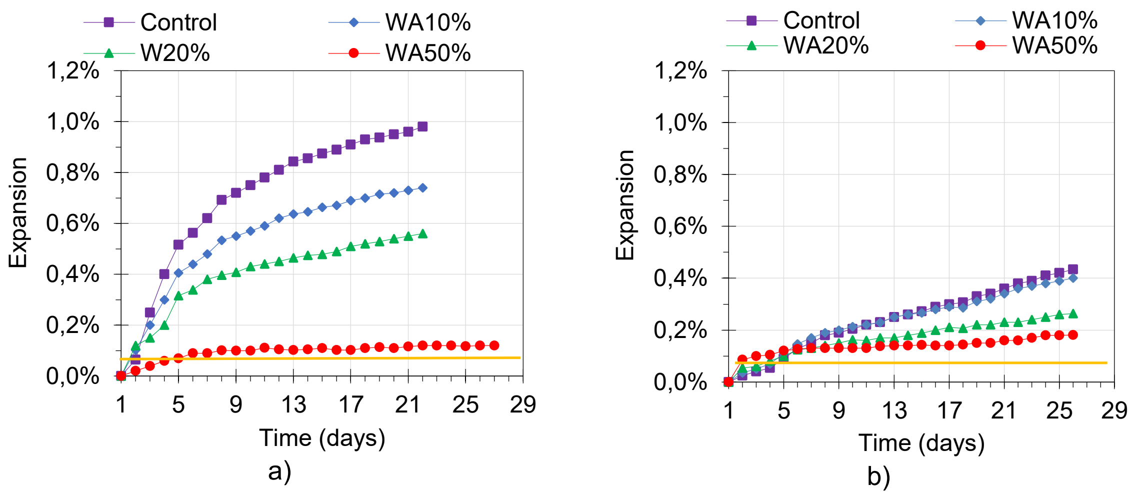


Figure 5.1: Accelerate Mortar Bar Test (AMBT) expansion of ASR-affected mortars: a) Polymictic Fine (Tx) and b) Greywacke Crushed Coarse (SPH).

Figure 5.2 shows the specimens' expansions obtained through the ACPT as a function of time, in which Figure 5.2a) illustrates Tx sand results while Figure 5.2b) displays SPH data. In general, the mixtures containing Tx presented a faster kinetics than those incorporating SPH, as obtained from mortar bars. However, differently from the AMBT, the influence of WA on ASR-induced development was ambiguous. For concrete incorporating SPH, the higher the WA replacement, the higher was the expansion obtained at 45 days.

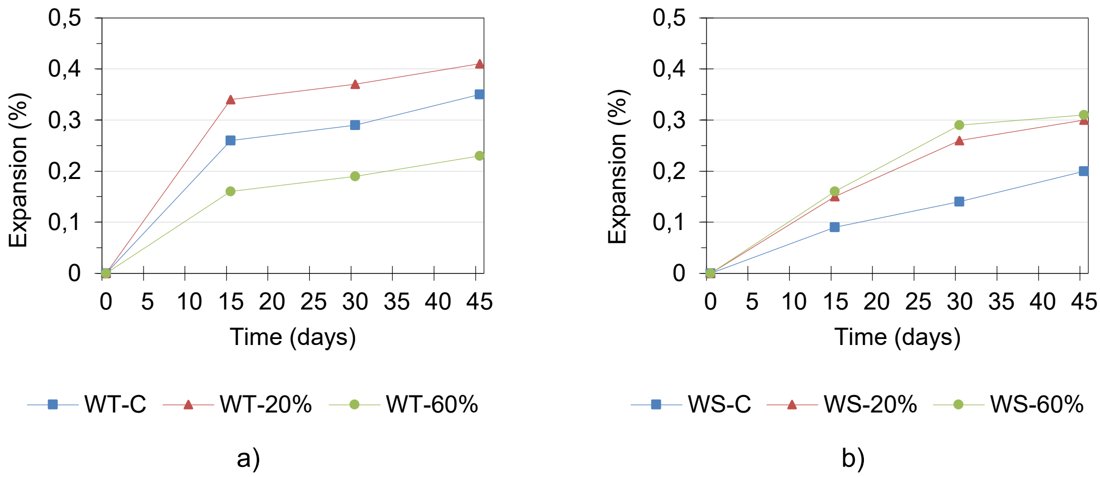


Figure 5.2: Accelerated Concrete Prism Test (ACPT) expansion of ASR-affected samples cured at 60°C and 100% of R.H.: a) Polymictic Fine (Tx) and b) Greywacke Coarse (SPH).

5.2 Mechanical properties assessment

This section evaluates the losses in modulus of elasticity and compressive strength of the various concrete mixtures investigated. The mechanical data presented here, displays the ratio of values obtained at each selected "free" expansion level over the values obtained on sound concrete specimens, presenting an "equivalent maturity" than the damaged samples as previous discussed in 4.2. Figure 5.3 shows a) the variation (in percentage) among the mechanical properties (compressive strength and modulus of elasticity) of ASR-affected concrete specimens, and b) the stiffness damage index obtained with the samples at 30 days of exposure.

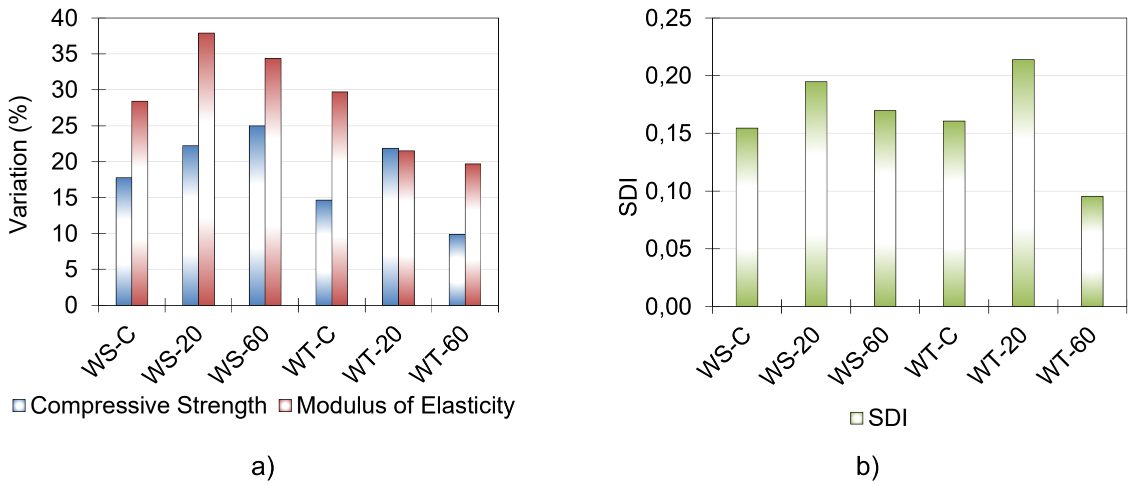


Figure 5.3: Assessment of the mechanical properties of the concrete samples: a) Variation percentage in Compressive Strength and Modulus of Elasticity; b) Stiffness Damage Index

In general, the compressive strength (CS) was found to decrease in a somewhat modest way in comparison with the modulus of elasticity. On average, CS values of WS-20 and WS-60 lessened 22% and 25%, which represents a drop of 25% and 41% when compared to the control group (WS-C), respectively. Conversely, WT mixes displayed lower losses in CS than WS (i.e. 27.1% lower than the control group, on average) even for the highest expansion level measured. Moreover, samples made of Tx sand behaved in a somewhat different way than those made of Springhill aggregate; i.e. WT-20 showed higher CS loss (i.e. 22.5%) than the control mixture whereas WT-60 behaved better (only 10% reduction).

In terms of modulus of elasticity (ME), WS mixtures presented the highest loss while replacing 20% of PC by WA; i.e. on average, E dropped about 38% and 34% for WS-20 and WS-60, which represents 35% and 21% higher than the control group (WS-C), respectively. On the other hand, WT mixtures were found to have a different behaviour; the higher the WA replacement, the lower the loss in stiffness (i.e. WT-20 and WT-60 showed 28% and 34% lower modulus of elasticity than WT-C, respectively).

Figure 5.3.b) illustrates the SDI results obtained through the *stiffness damage test* (SDT) method, in accordance with Sanchez et al. [6,25,26]. Overall, the SDI results obtained were quite similar to the pattern of CS and ME outcomes in both mixtures. For WS mixes, the lowest SDI value was found on WS-C, with 0.15, then for WS-20 and WS-60 the SDI results obtained were 0.19 and 0.17 respectively. Differently from WS mixtures, the WT-C did not obtain the lowest SDI value, displaying a SDI result of 0.16, while, for WT-20 and WT-60 the results obtained were 0.21 and 0.10 respectively.

5.3 Microscopy Assessment

Figure 5.4 presents the microscopic damage features and DRI numbers obtained from the ASR-affected concrete specimens over 30 days of exposure, considering the aggregates type Tx and SH with different amounts of WA.

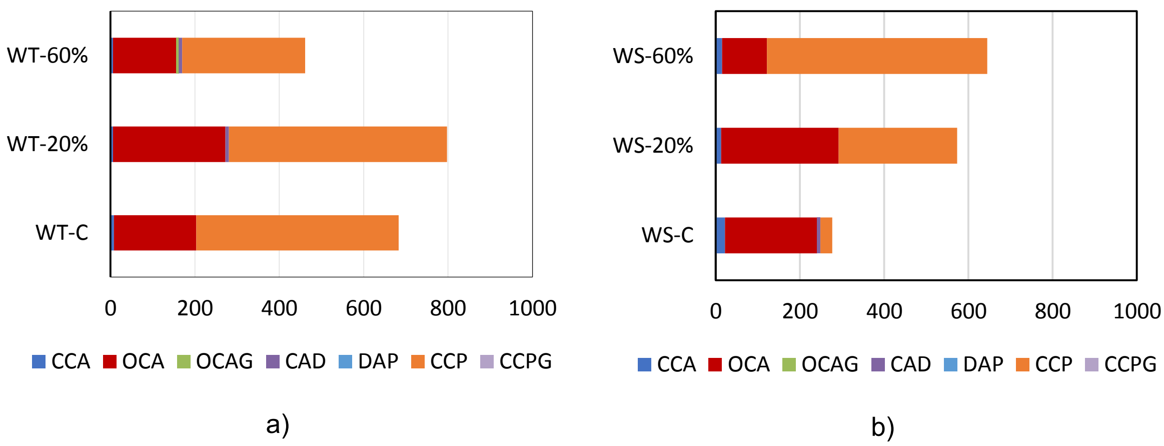


Figure 5.4: Damage Rating Index for the ASR-affected concrete specimens: a) Polymictic Fine (Tx) and b) Greywacke Coarse (SPH).

Figure 4.4 provides the DRI number as a function of the WA replacement for the mixtures incorporating both types of aggregates used. Figure 4.4 a) illustrates the DRI numbers for Tx mixes while Figure 4.4 b) displays SPH mixtures results. As expected, a quite high DRI number was observed for WT mixtures, both control and WT-20%. The DRI numbers ranged from 700 to 800. However, using 60% of WA reduced significantly the DRI number down to 430. Moreover, for these mixtures important cracks were observed within the aggregate particles and cement paste, as expected. The presence of important amount of gel was not observed. On the other hand, the results from mixtures made of SPH showed a completely opposite behaviour; the higher the WA replacement, the higher the damage observed.

6. DISCUSSION

6.1 ASR-kinetics and induced development

According the Accelerated Mortar Bar Test – (AMBT), it is clear that replacing PC by wood ash, ASR-induced development is lower; i.e. the higher the replacement level, the lower ASR-induced development. Additionally, replacing 50% of PC by WA, one may notice that Tx reactivity is mitigated down to a non-reactive behaviour as per ASTM C 1260, whereas the mixture proportioned with SPH showed expansion levels slightly above the limit (0.10% at 14 days in solution). These results are consistent with results found in the literature for SCMs with high calcium content such as WA [5]. Conversely, specimens tested in the ACPT did not display the same ASR-induced development.

In the case of WS mixtures, ACPT results indicated almost “exactly” the opposite behaviour when compared to AMBT; i.e. the higher the replacement level, the higher the ASR kinetics and induced expansion at 45 days. Yet, the final expansion at 45 days for WS-20 and WS-60 were very similar (i.e. ≈ 0.30%). The latter evidences that worst behaviour of mixtures incorporating WA. However, mixtures made of Tx (known to be more reactive than SPH as per the CPT test) did not display the same behaviour, since an incorporation of 20% of WA made the induced expansions to be worse than the control mix (i.e.0.40%) at 45 days, while the replacement of 60% decreased the final expansion in about 34% (i.e.0.23%) at the same time period.

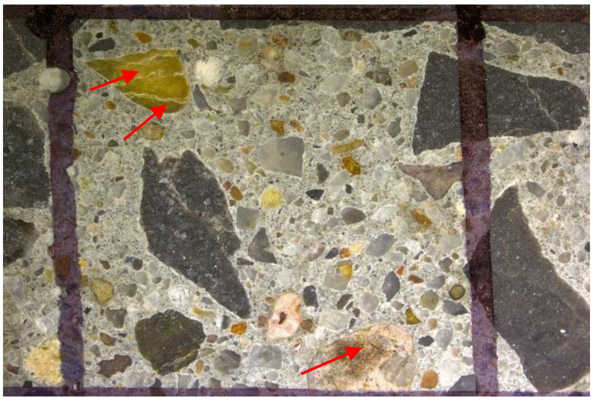
The results above emphasize that the reactive behaviour of mixtures made of WA depend on the aggregate type and nature (i.e. five vs coarse, lithotype, reactivity degree, etc.), since very distinct performance was obtained for the same replacement level while the use of distinct aggregates. Moreover, the results obtained in this work clearly indicate the incompatibility between the AMBT and ACPT tests for assessing the efficiency of preventive measures to mitigate ASR-induced expansion and development. Hence, the interesting results gathered through the AMBT could be simply a “false negative” behaviour as previously reported in the literature [28]. Further research is required in this regard.

6.2 Mechanical and microscopic assessment

Mechanical and microscopic analyses were performed to assess the extend of damage of the ASR affected mixtures. In general, the results agreed with the expansion levels obtained (i.e. the higher the expansion level, the higher the losses in mechanical properties). Yet, the type and nature of the reactive aggregate showed to play an important role on the reaction kinetics and distress development.

Even though the WT mixtures developed higher expansion levels than WS, the losses in the mechanical properties did not follow the same trend. However, this behaviour was quite expected, since coarse aggregates have more influence in the concrete mechanical properties, particularly in the stiffness or modulus of elasticity. Furthermore, the DRI results presented in Figure 5.4 showed evidences that more open cracks in the aggregates were found in WS specimens, which may explain the higher loss of ME obtained. Likewise, the total number of cracks obtained through DRI increases proportionally with the increase in PC’s replacement level, the only exception was WT-60. This exception might be explained by the image presented in the Figure 6.1-c, where most of the pores are filled with gel, and there is few cracks in the cement paste, meaning that the gel is being storage in these pores and due the changes in gel viscosity that is not expanding, therefore, avoiding crack propagation. Besides, it was observed that samples containing WA developed faster crack propagation through the cement paste, which may be explained by the WA particle features (i.e. high alkali, high pores and low SiO2) used in this research, as observed in Figures 6.1 and 6.2. These results corroborate with the SDI findings which indicates that PC’ replacement by WA did not decrease the ASR-induced damage.

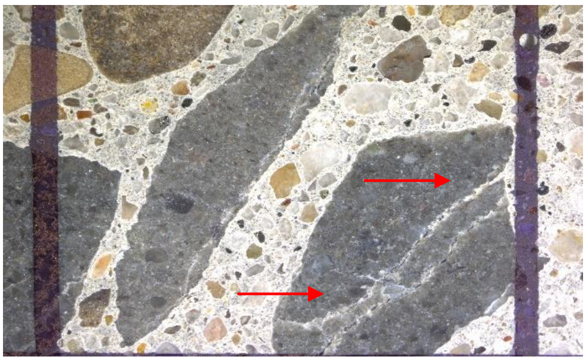
Figure 6.1a (WT-C specimen) reveals several OCA features in the non-reactive coarse aggregate besides the significant increase in the number of cracks coming from the reactive polymictic fine. Yet, WT-20 (Figure 6.1b) and WT-60 (Figure 6.1c) indicates notable decrease in the quality of the microstructure since more pores were detected and thus thin cracks may have been originated from a different mechanism than ASR (e.g. shrinkage). Nevertheless, following the minimum energy law, WA particles display low mechanical properties and high porosity which may explain the fact that several cracks propagated through the coarser WA particles. Moreover, it has been observed for both WT-20 and WT-60 specimens a notable number of pores filled by ASR-gel; furthermore, most of the cracks were already connected to each other, which indicates that the samples containing WA were further damaged. Finally, WS-C (Figure 6.2a), WS-20 (Figure 6.2b) and WS-60 (Figure 6.2c) displayed similar evidences as aforementioned for WT mixtures, yet the coarse aggregate contributed more towards the cracks propagation and distress, as expected.


a)


b)


c)

Figure 6.1 : Pictures captured during the DRI test for mixtures incorporating Tx sand: a) WT-C; b) WT-20% and c) WT-60%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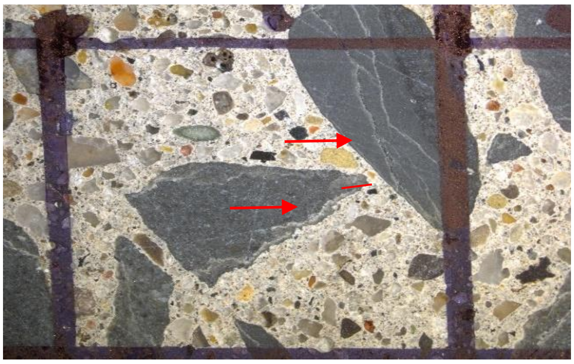
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Figure 6.2: Pictures taken over the DRI analyses for mixtures incorporating SPH coarse aggregate: a) WS-C; b) WS-20% and c) WS-60%

7. CONCLUSION

The main objective of the research was to determine the influence and efficiency of different amounts of WA to supress ASR-induced expansion and damage. The main findings of the current research are presented hereafter:

- The accelerated mortar bar test (AMBT), showed that the higher the replacement level of PC by WA, the lower the expansion levels reached by mixtures incorporating highly reactive Tx and SPH aggregates. Mixtures made with 50% WA replacement were considered either non-reactive or just above the reactivity limit as per ASTM C 1260-1567 for both Tx and SPH aggregates, respectively.

- The results obtained through the ACPT are not in agreement with the results obtained through the AMBT for both aggregates used. The latter seems to indicate an example of a "false negative" result yielded by the accelerated mortar bar test. The ACPT results found for the SPH aggregate seem to be counterintuitive since the higher the amount of WA replacement, the higher the distress obtained. Further analyses are still required to fully understand this topic.

- The mechanical properties losses (i.e. compressive strength, modulus of elasticity and SDT) are in agreement with the expansion levels obtained and microscopic analyses conducted through the DRI method. Although the mechanisms observed while the use of WA seems to change as a function of the aggregate type and may be somewhat counterintuitive, the use of the multi-level assessment clearly indicated the expansion results obtained were correct.

- The preliminary results obtained in this research seem to indicate that WA is not a suitable material to be used as an SCM to mitigate ASR-induced development in concrete. Yet, trials should still be conducted to use such a material as a filler or even tailing towards to decrease the carbon footprint of concrete construction, a greener future in civil engineering.

8. REFERENCES

[1] B. Fournier, M.A. Bérubé, Alkali-aggregate reaction in concrete: A review of basic concepts and engineering implications, Can. J. Civ. Eng. 27 (2000) 167–191. https://doi.org/10.1139/l99-072.

[2] L.F.M. Sanchez, B. Fournier, M. Jolin, J. Bastien, Evaluation of the stiffness damage test (SDT) as a tool for assessing damage in concrete due to ASR: Test loading and output responses for concretes incorporating fine or coarse reactive aggregates, Cem. Concr. Res. 56 (2014) 213–229. https://doi.org/10.1016/j.cemconres.2013.11.003.

[3] B. Fournier, M.-A. Bérubé, Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications, Can. J. Civ. Eng. 27 (2000) 167–191. https://doi.org/10.1139/cjce-27-2-167.

[4] T. Katayama, The so-called alkali-carbonate reaction (ACR) - Its mineralogical and geochemical details, with special reference to ASR, Cem. Concr. Res. 40 (2010) 643–675. https://doi.org/10.1016/j.cemconres.2009.09.020.

[5] J. Lindgård, Ö. Andiç-Çakir, I. Fernandes, T.F. Rønning, M.D.A. Thomas, Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing, Cem. Concr. Res. 42 (2012) 223–243. https://doi.org/10.1016/j.cemconres.2011.10.004.

[6] L.F.M. Sanchez, Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction, (2014) 341.

[7] M. Thomas, The effect of supplementary cementing materials on alkali-silica reaction: A review, Cem. Concr. Res. 41 (2011) 1224–1231. https://doi.org/10.1016/j.cemconres.2010.11.003.

[8] D.J. de Souza, L.F.M. Sanchez, M.T. de Grazia, Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete, Constr. Build. Mater. 229 (2019) 116806. https://doi.org/10.1016/j.conbuildmat.2019.116806.

[9] Z. Shi, C. Shi, J. Zhang, S. Wan, Z. Zhang, Z. Ou, Alkali-silica reaction in waterglass-activated slag mortars incorporating fly ash and metakaolin, Cem. Concr. Res. 108 (2018) 10–19. https://doi.org/10.1016/j.cemconres.2018.03.002.

[10] J. Duchesne, M.-A. Bérubé, The Effectiveness Of Supplementary Cementing Materials In Suppressing Expansion Due To Asr: Another Look At The Reaction Mechanisms Part 1: Concrete Expansion And Portlandite Depletion, Cem. Concr. Res. 24 (1994) 221–230.

[11] Y. Kawabata, K. Yamada, The mechanism of limited inhibition by fly ash on expansion due to alkali–silica reaction at the pessimum proportion, Cem. Concr. Res. 92 (2017) 1–15. https://doi.org/10.1016/j.cemconres.2016.11.002.

[12] A.M. Boddy, R.D. Hooton, M.D.A. Thomas, The effect of the silica content of silica fume on its ability to control alkali-silica reaction, Cem. Concr. Res. 33 (2003) 1263–1268. https://doi.org/10.1016/S0008-8846(03)00058-9.

[13] M.C.G. Juenger, C.P. Ostertag, Alkali-silica reactivity of large silica fume-derived particles, Cem. Concr. Res. 34 (2004) 1389–1402. https://doi.org/10.1016/j.cemconres.2004.01.001.

[14] A. Leemann, L. Bernard, S. Alahrache, F. Winnefeld, ASR prevention - Effect of aluminum and lithium ions on the reaction products, Cem. Concr. Res. 76 (2015) 192–201. https://doi.org/10.1016/j.cemconres.2015.06.002.

[15] J. Wei, B. Gencturk, A. Jain, M. Hanifehzadeh, Mitigating alkali-silica reaction induced concrete degradation through cement substitution by metakaolin and bentonite, Appl. Clay Sci. 182 (2019) 105257. https://doi.org/10.1016/j.clay.2019.105257.

[16] E.R. Teixeira, A. Camões, F.G. Branco, Valorisation of wood fly ash on concrete, Resour. Conserv. Recycl. 145 (2019) 292–310. https://doi.org/10.1016/j.resconrec.2019.02.028.

[17] C.B. Cheah, M. Ramli, The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An overview, Resour. Conserv. Recycl. 55 (2011) 669–685. https://doi.org/10.1016/j.resconrec.2011.02.002.

[18] R. Siddique, Utilization of wood ash in concrete manufacturing, Resour. Conserv. Recycl. 67 (2012) 27–33. https://doi.org/10.1016/j.resconrec.2012.07.004.

[19] A.U. Elinwa, S.P. Ejeh, A.M. Mamuda, Assessing of the fresh concrete properties of self-compacting concrete containing sawdust ash, Constr. Build. Mater. (2008). https://doi.org/10.1016/j.conbuildmat.2007.02.004.

[20] S. V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, An overview of the chemical composition of biomass, Fuel. 89 (2010) 913–933. https://doi.org/10.1016/j.fuel.2009.10.022.

[21] L. Etiégni, A.G. Campbell, Physical and chemical characteristics of wood ash, Bioresour. Technol. (1991). https://doi.org/10.1016/0960-8524(91)90207-Z.

[22] T.R. Naik, R.N. Kraus, R. Siddique, Controlled low-strength materials containing mixtures of coal ash and new pozzolanic material, ACI Mater. J. 100 (2003) 208–215. https://doi.org/10.14359/12621.

[23] F.F. Udoeyo, H. Inyang, D.T. Young, E.E. Oparadu, Potential of Wood Waste Ash as an Additive in Concrete, J. Mater. Civ. Eng. 18 (2006) 605–611. https://doi.org/10.1061/(ASCE)0899-1561(2006)18.

[24] F.F. Udoeyo, P.U. Dashibil, Sawdust ash as concrete material, J. Mater. Civ. Eng. 14 (2002) 173–176. https://doi.org/10.1061/(ASCE)0899-1561(2002)14:2(173).

[25] L.F.M. Sanchez, B. Fournier, M. Jolin, J. Bastien, Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses, Constr. Build. Mater. 77 (2015) 20–32. https://doi.org/10.1016/j.conbuildmat.2014.11.071.

[26] L.F.M. Sanchez, T. Drimalas, B. Fournier, D. Mitchell, J. Bastien, Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms, Cem. Concr. Res. 107 (2018) 284–303. https://doi.org/10.1016/j.cemconres.2018.02.017.

[27] L.F.M. Sanchez, B. Fournier, M. Jolin, M.A.B. Bedoya, J. Bastien, J. Duchesne, Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate, ACI Mater. J. 113 (2016) 395–407. https://doi.org/10.14359/51688983.

[28] N. Goshayeshi, Contribution to the development of analytical models to forecast alkali-aggregate reaction (AAR) kinetics and induced expansion in Civil Engineering, (2019).