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Studies on the Fresh Properties and Long Term Performance of Unshrinkable Fill Containing Reclaimed Concrete Aggregate (RCA)

Maryam Kolahdoozan, Mohamed Lachemi and Medhat Shehata
(Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada)
And
Hannah Schell, Stephen Senior and Carole Anne MacDonald
(Ministry of Transportation, Ontario)

Abstract: This paper investigates the possibility of producing Unshrinkable Fill (U-fill) using alternative aggregate sources, namely reclaimed concrete aggregate (RCA). In order to ensure compliance with current standards for U-fill, several mixtures were produced and tested for physical properties including flowability, hardening time and strength. Field trial observations of optimized mixes have shown that using 100% RCA in U-fill mixes could extend the hardening time or time-to-loading. Therefore gravel and sand were used along with RCA in order to provide for faster dissipation of mixing water, enabling the mix to carry load after a relatively short period of time. The chemical properties of RCA are also investigated in this paper. It had been determined from earlier observations that expansion due to internal sulphate attack can cause failure in the paste of mortars containing high percentages of sulphate. To confirm, mortar bars were prepared using RCA aggregate with added sulphate contents ranging from 0.5 to 3.5 % SO_4 (increasing in increments of 0.5) by mass of RCA. Periodic measurements showed high rates of expansion in mortars containing 2.5, 3.0 and 3.5% SO_4. These bars were analysed using scanning electron microscopy, which indicated the presence of solid solution of thaumasite and ettringite. The limiting level of sulphate to ensure that the test samples did not suffer sulphate attack was found to be 1.5% SO_4 by mass of RCA.

1. Introduction

Unshrinkable fill is one of the most frequently used materials in construction, pavement and utility repair projects. U-fill, as it is commonly known, can be described as a highly flowable, low strength, cementitious construction material. One of the main advantages of U-fill is its ease of placement, and future excavation. Due to its high flowability and low strength, it is an ideal mix to use in narrow trenches or more generally in areas where placing and compacting is difficult (PCA, 2009). It is usually recommended that the maximum strength of these mixes to be limited to 0.4 MPa at 28 days (OPSS 1359, 2006). Drainage of water from the U-fill mixes and hardening times are important factors to be considered when designing U-fill mixes. It is usually preferred to specify the hardening time to less than one hour in order to allow traffic operation to resume safely. In order to minimize hardening time, aggregate gradations should be optimized to allow for fast dissipation of internal mix water. This can only be done through the evaluation of trial mixes and examination of aggregate gradation curves. Other factors such as permeability of the surrounding soil and the ambient conditions during the time of placement can also either increase or decrease the rate of water drainage (Folliard et.al. 2008). Where hardening time needs to be kept to a minimum, it is best to remove any existing water within trenches where the U-fill mix is to be placed.

2. Scope of work

The objective of this paper is to investigate the possibility of using Reclaimed Concrete Aggregate (RCA) in U-fill mixes while maintaining properties such as flowability, hardening time and strength. Due to increasing cost and shortage in supplies of high quality virgin aggregate, the demands for using alternative aggregates in construction applications has been increasing. As a result, materials such as RCA have become a more appealing option to use in various types of construction projects. Using RCA can promote sustainability while reducing costs and energy consumption. In the following sections, the feasibility of using various percentages of RCA in U-fill applications will be further discussed and analyzed. The effects of sulphate on the durability of U-fill mixes will also be investigated.

3. Outline of experimental program

3.1 Material properties

Three aggregates, namely returned-to-plant RCA, uncrushed gravel and natural sand were used in this experimental program; the properties of each are summarized in the table below:

Table 1: Physical Properties of Gravel, sand and RCA

	Gravel	Sand	RCA
Bulk Specific Gravity (kg/m^3)	2.658	2.719	2.254
Bulk Specific Gravity, SSD (kg/m^3)	2.688	2.749	2.423
Apparent Specific Gravity (kg/m^3)	2.711	2.805	2.7115
Absorption (%)	1.08	1.12	7.58

Preliminary mix results showed that using 100% RCA aggregate in the mixes resulted in segregation of fines and an increase in hardening time. Therefore to obtain more desirable fresh and hardened properties, gravel and sand were added to the mix. The properties of each mix will be further discussed in the following sections. The gradations for each aggregate type are shown in Figure 1. It should be noted that RCA contains both coarse and fine fractions.

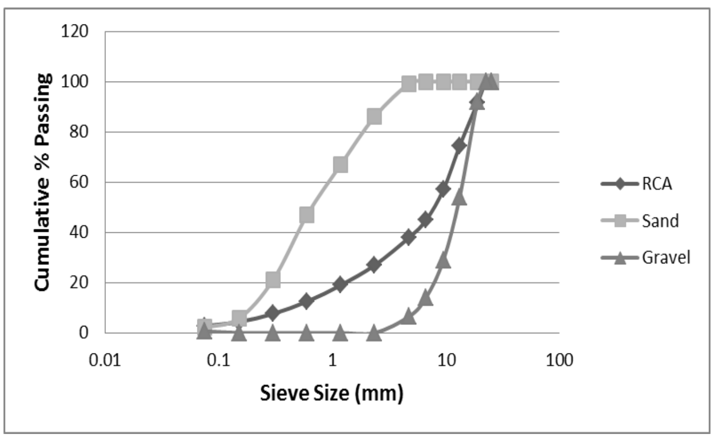

Figure 1: Grain size distribution of RCA, Sand and Gravel

As RCA aggregate contain a considerable amount of residual paste, it was imperative to determine the amount of increase in fines due to abrasion during mixing in order to be able to accurately predict the performance of the Unshrinkable fill product. Bleeding, segregation, drainage and hardening time are highly dependent on the amount of sand-sized fraction in the mix. In order to determine the abrasion resistance, coarse and fine (passing 4.75mm sieve) portions of the RCA aggregate were tested using the Micro-Deval abrasion test (MDA). The results are listed in Table 2. The results provide an indication of the relative amounts of fines that are likely to be produced during mixing. Higher loss indicates that higher levels of fines are produced during extended mixing. The maximum allowable MDA loss specified for granular base coarse aggregates in Ontario (Granular A) are 25.0% for coarse aggregate and 30% for fine aggregate (OPSS 1010). For concrete aggregate, however, the limits are 17% and 20%, respectively. In Ontario, the current specification for U-fill requires the use of concrete aggregate in U-fill (OPSS 1002).

Table 2: Micro-Deval abrasion loss for RCA (LS618 & LS 619)

	RCA (Coarse)			RCA (Fine)		
Trial #	**Initial (g)**	**Final (g)**	**Percent Loss (%)**	**Initial (g)**	**Final (g)**	**Percent Loss (%)**
Trial #1	1474	1119	24.1	500	353	29.4
Trial #2	1484	1110	25.2	501	347	30.7
Trial #3	1494	1108	25.8	502	330	34.3
		Average =	**25.03%**		**Average=**	**31.46%**

The effects of increase in fines and sand-size fractions due to abrasion of RCA aggregate on the performance of U-fill mixes will be further discussed in the following sections.

3.2 Preparation of Laboratory and Field Trial Batches

3.2.1 Phase I

The following two sets of laboratory mixes were prepared in order to determine the feasibility of producing U-fill containing only RCA aggregate:

- 1700-1850 kg/m^3 RCA, 25 kg/m^3 type GU Portland cement and water contents of 160, 185 and 220 kg/m^3 (Mix #1, 2 & 3).
- 1700-1830 kg/m^3 RCA, 25 kg/m^3 of Ground granulated blast furnace slag (no Portland cement), and water contents of 160, 185 and 220 kg/m^3 (Mix #4,5 &6). Ground granulated blast furnace slag (GGBFS) was investigated as a sustainable and economical alternative for Portland cement.

To further evaluate the performance of each mix, field tests were done using optimized mixes from each set and evaluated for their fresh and hardened properties. A total of three trenches were excavated into stiff, clay soil, locally known as the Halton Till, a thick over consolidated glacial deposit characterized by poor drainage. Each trench had an approximate size of 2.5m^3. Batches were poured in after approximately 10 minutes of mixing time.

To measure hardening time, the ball drop test as per ASTM D6024 was used. A ball drop apparatus with a weight of 14-15 kg was set upon two 9X9X18 cm wooden blocks. The mixes were considered hardened when the indentation left by the ball drop apparatus was less than 76 mm in diameter. For lab mixtures, the U-fill was cast and tested in wooden blocks of the dimension 70x 45x13 cm. For the field trenches, the test was done on the trench after filling it with the U-fill

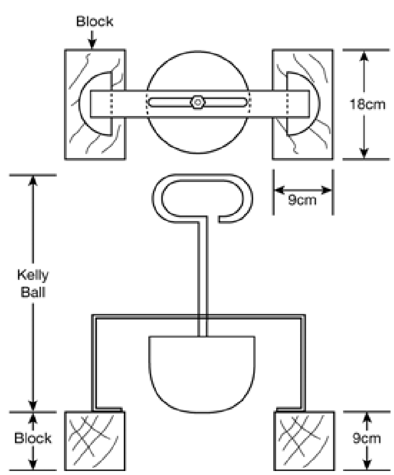

Figure 2: Ball drop apparatus for measuring hardening time (ASTM C6024)

3.2.2 Phase II

In order to enhance the fresh and hardened properties, particularly in terms of achieving shorter hardening time, mixes were modified using various percentages of gravel, sand and RCA. Mixes in this phase were made with the aim of achieving a quicker hardening time while maintaining minimal segregation and high flowability. The first five mixes were produced using RCA and gravel only. The mix proportions were as follows:

Table 3: Phase II lab mixes containing RCA & gravel

Mix #	RCA	Gravel	Water (kg/m^3)
7	70%	30%	180
8	70%	30%	220
9	50%	50%	220
10	80%	20%	185
11	80%	20%	220

For all the above mixtures, the Portland cement content was 25 kg/m^3 and the RCA and gravel are expressed as % of total aggregate content.
It was observed from these mixes that more fine aggregate is required to further reduce segregation. Therefore sand was also incorporated into three mixes with the following proportions:

Table 4: Phase II mixes containing gravel, RCA & sand

Mix #	Gravel	RCA	Sand	Water (kg/m^3)
12	50%	30%	20%	220
13	40%	30%	30%	220
14	30%	40%	30%	220

Portland cement was kept at 25 kg/m^3 and water was adjusted to obtain the required workability (a minimum of 150 mm slump). The hardening time and flowability of each mix was evaluated. Optimized mixes produced from the combination of the three aggregates were then tested in a field trial and compared to results obtained from lab mixes.

3.3 Expansion due to internal sulphate attack

Other than the physical properties of the mixes, the chemical stability was also investigated. This was done in an attempt to find out how different percentages of internal sulphate may affect the performance of U-fill mixes and to find the maximum percentage of sulphate content below which significant deterioration due to sulphate attack does not occur. The forms of sulphate attacks investigated were ettringite and thaumasite formation.
In order to measure for expansion due to thaumasite and ettringite formation, mortar bars were prepared using a modified version of ASTM C452. Since cement content in U-fill mixes is much lower than that in conventional concrete or in standard mortar bars, an aggregate to cement ratio of 11:1 and a water-cement ratio of 1.9, excluding the absorption of aggregate, was used instead of the specified 2.75:1 aggregate to cement ratio and 0.485 water- cement ratio. The bars were then stored in saturated lime water solution and stored at room temperature to measure expansion due to ettringite, and at 5˚C to measure expansion due to thaumasite formation. The bars were measured periodically in accordance to ASTM C157.

A total of seven sets of mortar bars were made with sulphate contents ranging from 0.5 to 3.5% SO_4 by mass of aggregate, increasing in increments of 0.5%. In order to compensate for the high absorption of RCA, the water-to-cement ratio of these bars were increased to 2.9. From a parallel experimental program on similar materials, it was determined that expansion due to thaumasite is much higher than that due to ettringite formation at a given age, therefore the bars were stored at 5 ˚C and measured periodically.

4. Results and Discussion

4.1 Phase I Mix results

As mentioned in section 3.2.1, two trial mixes were prepared in this stage using only RCA aggregate. One set of mixes were prepared using Portland cement and the other with GGBFS. Results obtained from mixes made with Portland cement were all in compliance with standards specified by OPSS 1359. As it can be seen from Table5, strength of test samples decreases with an increase in water content, less segregation and a more uniform dispersion of fines were seen in samples containing 220 kg/m^3.

Table 5: Phase I-Cement mix results

Mix #	Cement Content (kg/m^3)	Water Content (kg/m^3)	Slump (mm)	7 Day Strength (MPa)	28 Day Strength (MPa)
1	25	160	155	0.035	0.116
2	25	185	162	0.030	0.096
3	25	220	175	0.015	0.087

Proportions of the mixes made with slag were equivalent to mixes containing cement. Similar results were seen with these mixes as well. Strength results at 7 and 28 days were slightly higher than the mixes containing cement; however the difference is negligible considering the variables associated with measuring such low strength levels.

Table 6: Phase I- Slag mix results

Mix #	Slag Content (kg/m^3)	Water Content (kg/m^3)	Slump (mm)	7 Day Strength (MPa)	28 Day Strength (MPa)
4	25	160	150	0.092	0.254
5	25	185	165	0.084	0.192
6	25	220	180	0.077	0.119

A field trial was carried out using mix number 2 from Table 5 with 185 kg/m^3 water and mix number 6 from table 6 with 220 kg/m^3. Water contents for each mix were selected based on the amount of water existing within the trench prior to pouring. From the trial, it was observed that both mixes showed a longer than expected hardening time. It is hypothesized that RCA, due to its hygroscopic properties and high absorption, prevents water from draining out of the mix. Results from the field trial are summarized in Table 7. As expected both 7 day and 28 day strengths are below the 0.4 MPa limit.

Table 7: Results from first field trial

Mix #	Type	7 Day Strength	28 Day Strength	Hardening Time
2 (from Table 5)	Cement & RCA	0.22 MPa	0.33 MPa	≈44 hours
6 (from Table 6)	Slag & RCA	0.19 MPa	0.26 MPa	≈21 hours

Figure 3: Slag and RCA mix (left) cement &RCA mix (right). Note that the excessive water in the slag mix is attributable to the presence of water in the trench prior to placement of the U-fill mix

4.2 Phase II mix results:

In order to reduce hardening time and enable fast draining of water, new mixes were produced by incorporating gravel to the mix (Table 8). Due to their low strength, these mixes could not be demoulded for strength measurement. They also showed high segregation due to the increased percentage of coarse aggregate.

Table 8: Stage I mixes (lab results)

Mix #	Aggregate combination	Water content (kg/m^3)	Cement content (kg/m^3)	Slump (mm^2)
7	70% RCA & 30% Gravel	180	25	190
8	70% RCA & 30% Gravel	220	25	190
9	50% RCA & 50% Gravel	220	25	220
10	80% RCA & 20% Gravel	185	25	180
11	80% RCA & 20% Gravel	220	25	195

** Hardening time for the above mixes were not measured as segregation was observed in all except for mixes containing 70%RCA & 30%Gravel.The hardening time for this mix with 220 kg/m^3 was tested in stage II (table 9).*

Based on observation from the gravel and RCA mixtures, it was decided to add sand to the mixtures. This resulted in mixtures with better performance in terms of segregation and hardening time. It was also found that the hardening time increases with an increase in amount of RCA (Table 9). The reasons behind the effect of RCA on hardening time are not yet fully understood. It appears that factors other than the high absorption of RCA affect the rate of water drainage from the fresh mix. Increased fines may have been generated during the mixing process at the batch plant or in the transport vehicle due to the low abrasion resistance of RCA. The high ability of such fines to retain water through increased absorption and adsorption capacity could be a contributing factor.

Table 9: Stage II mixes (lab results)

Mix #	Gravel	RCA	Sand	Cement (kg/m^3)	Water (kg/m^3)	Hardening time (min)
12	50%	30%	20%	25	220	20
13	40%	30%	30%	25	220	35
14	30%	40%	30%	25	220	40
15	30%	70%	---	25	220	50

The three mixes selected for the second field trial are summarized in Table 10. Due to the poor drainage properties of the surrounding Halton Till, water dissipated at a much lower rate than the lab mixes which were tested in wooden boxes (Table 9). Therefore, to further reduce the hardening time, the third mix was batched using 70% gravel, 20% RCA and 10% sand (mix 16). However, the hardening time for this mix was higher than the mix containing 50% gravel, 30% RCA and 20% sand (mix 12 from Table 9). The reason behind this increase in hardening time could be attributed to the fact that during mixing, abrasion of the RCA causes an increase in fines and thus an increase in hardening time. As seen in table 2, the MDA losses of the RCA used in these experiments were relatively high. This could have increased the total fines in the mixtures resulting in lower water dissipation from the fresh fill. Therefore it is necessary to find the correct proportions of fine and coarse aggregate and examine various trial mixes prior to finalizing them in order to be able to accurately predict the performance of U-fill produced with RCA.

Table 10: Results from second field trial

Mix #	Gravel	RCA	Sand	Water (kg/m^3)	Hardening time
15 (from table 9)	30%	70%	0%	220	≈5 hours
12 (from table 9)	50%	30%	20%	220	≈1 Hour
16	70%	20%	10%	200	≈3 Hours

Figure 4: Field trial mix containing 50% Gravel, 30% RCA & 20% Sand (Left) & Field trial mix containing 70% Gravel, 30% RCA & 20% Sand (Right)

4.3 Expansion due to internal sulphate attack

In the preliminary stage of this part of the experimental program, bars were made using the fine portion of granular aggregate containing 0.5% SO_4.The sulphate contents were then increased by adding gypsum to the paste. Sulphate contents for these bars ranged from 0.5% to 3.5% and were stored at 5˚C in lime water solution. It was assumed that the bars will expand mainly due to ettringite and thaumasite formation. Ettringite is formed when sulphate react with calcium aluminate present from the cement. This reaction can cause expansion and a decrease in bond between the paste and aggregate. In addition, sulphates can react with silica from the hydration products of cement (calcium silicate hydrates) in the presence of carbonate ions, and form Thaumasite. As a result of this reaction, the concrete paste breaks down into a mud-like paste. This form of internal sulphate attack is not limited to the level of alumina in the system.

Results from the sulphate testing has shown that due to loss of bond between aggregate and paste, bars containing > 2.0% SO_4 deteriorated at a much earlier age than bars with lower percentages of sulphate (Figure 5).From this graph it can be clearly seen that bars with up to 1.5% SO_4 experience a much lower and constant rate of expansion.

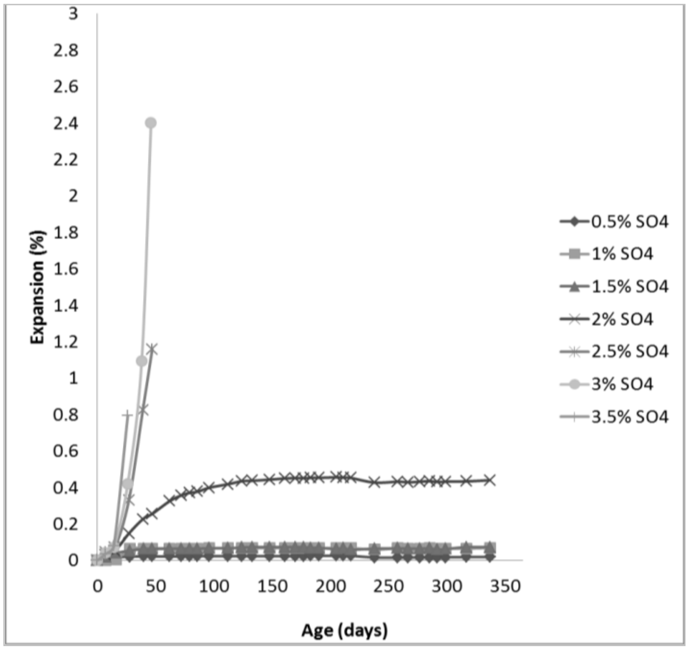

Figure 5: Expansion of mortar bars at various percentages of SO_4, stored in lime water solution

Figure 6 shows the expansion of mortars containing RCA mixed with various percentages of sulphate in the form of added gypsum. As it can be seen from Figure 6, the results show that with sulphate contents of 0.5,1 and 1.5% SO_4, expansion is insignificant, while at higher sulphate contents expansion increases considerably. From the results obtained from both tests, it can be concluded that internal sulphate attack is unlikely to be an issue with sulphate contents of up to 1.5% SO_4 by mass of aggregates.

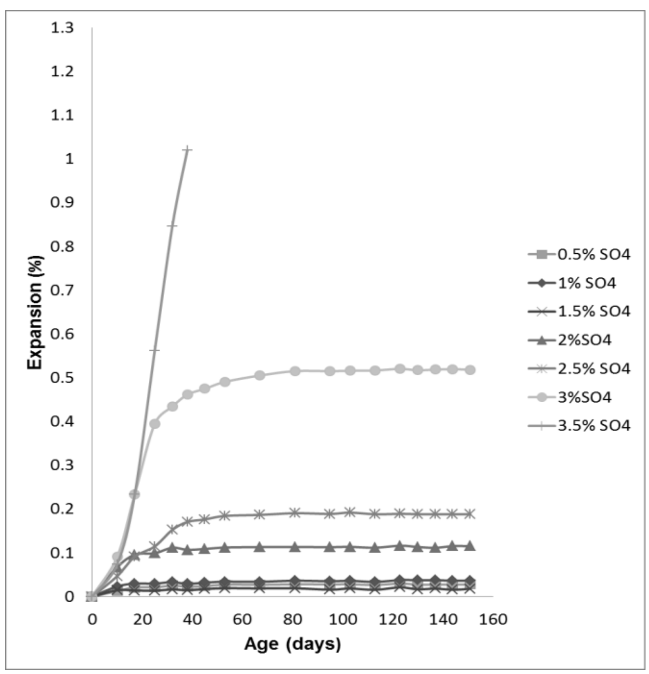

Figure 6: Expansion of RCA mortar bars at various percentages of sulphate

To find out the cause of expansion in the tested bars, analysis was done using scanning electron microscopy and energy dispersive x-ray analysis on bars containing 3.5% SO_4. The analysis showed the presence of solid phases of thaumasite and ettringite as presented in Figure 7.

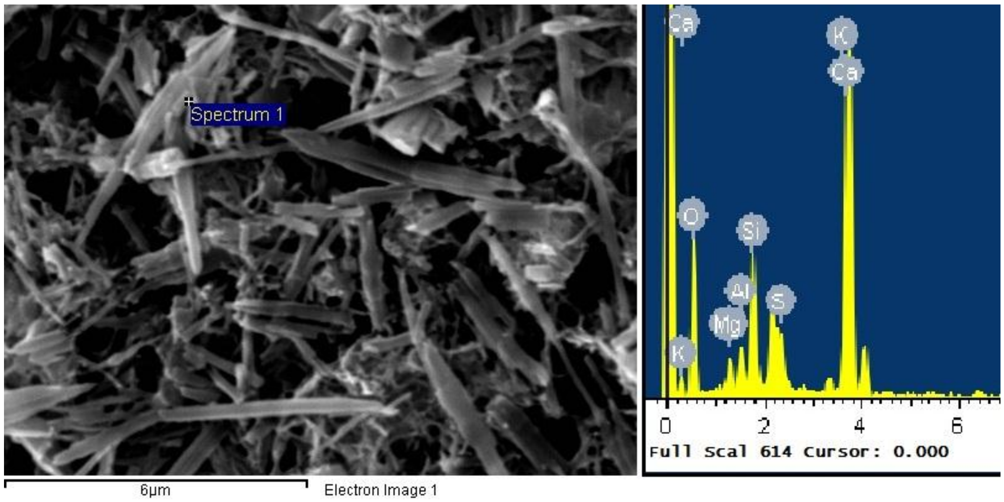

Figure 7: SEM results of mortar bars containing 3.5% SO_4

It should be born in mind that the mortar bar tested here were not of the same proportion as the U-fill. Indeed the ratio of cement to aggregate in U-fill is much lower than that in the bars tested in this paper. The 11:1 ratio used in the bars was the lowest aggregate/cement that could be used without breaking the bars during demoulding. Since Portland cement is the source of the main reactants to produce ettringite (Al_2O_3) and Thaumasite (SiO_2), one can argue that being of lower cement content, U-fill is less susceptible to internal sulphate attack than the bars used in this experimental program. On the other hand, the lower cement content of the U-fill could render it weaker than the bars; and hence, any level of sulphate attack can result in severe disintegration of the fill. While both arguments could be valid, the limit of SO_4 recommended here still provides a reasonable guideline of the upper limit of SO_4 content of aggregate intended to be used in U-fill. Performance of actual U-fill in terms of sulphate attack is a subject of future research at Ryerson University.

5. Conclusion

For the materials investigated in this study, the following conclusions are drawn:

1. Using 100% RCA aggregate to produce Unshrinkable fill mixes could result in an extended hardening time due to slow dissipation of mixing water.
2. The increase in fines due to mixing and abrasion of the RCA can further increase the water dissipation time.
3. It is recommended that a mixture of RCA, natural coarse aggregate and concrete sand be used to achieve desirable fresh U-fill mix properties.
4. Coarse aggregate and sand content of each mix should be adjusted based on the gradation of the RCA being used and the percent increase in fines due to abrasion.
5. Mortar bars tested at an aggregate to cement ratio of 11:1, and a water to cement ratio of 1.9, and soaked in a saturated solution of lime water, showed that sulphate contents as high as 1.5% SO_4 by mass of aggregate do not produce expansion due to internal sulphate attack (ettringite, thaumasite formation). Since U-fill mixes contain only 25 kg/m^3 of cement, the effects of thaumasite formation could be different than the bars investigated here; however, this requires further investigation.

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