Use of increasing amounts of bagasse ash waste to produce self-compacting concrete by adding limestone powder waste

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ABSTRACT

Bagasse ash is an abundantly available combustion by-product in the sugarcane industry. We examined the effect of adding limestone powder to self-compacting concrete mixtures in which large amounts of bagasse ash were employed as a fine aggregate replacement. A Type 1 Portland cement content of 550 kg/m³ was maintained in all of the mixtures. The fine aggregate was replaced with 10, 20, 40, 60, 80, or 100% bagasse ash and limestone powder by volume. Mixtures were designed to yield a slump flow diameter of 70 ± 2.5 cm. The workability (slump flow, T500, slump flow time, V-funnel flow time, and J-ring flow) and hardened properties (ultrasonic pulse velocity and compressive strength) of each mixture were measured, and blocking assessments were performed. The volumetric percentage replacement of 20% limestone powder in fine aggregate incorporating 20% bagasse ash effectively enhanced the workability and hardened properties of self-compacting concrete.

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1. Introduction

Sugarcane requires ample sunlight, warmth, and water, limiting its cultivation to semi-tropical regions. It is a particularly important product in developing countries (Wakamura, 2008). In 2011, the total worldwide production of sugarcane was approximately 1794 million tons. Thailand is the fourth largest producer of sugarcane in the world (Crop production, 2013), with a total production of 607,600 tons per year in Thailand. Fig. 1 is a flow chart of the raw sugar production process and the resulting by-products. Since refineries are normally built in locations where commercial power is unavailable, the factories generate their own electricity by burning bagasse to provide steam for back-pressure steam turbine generators as well as process heating (Wakamura, 2008). The resulting bagasse ash (BA) represents approximately 0.62% of the sugarcane weight (Cordeiro et al., 2004), or 607,600 tons per year in Thailand. Fig. 1 is a flow chart of the raw sugar production process and the resulting by-products.

In Thailand, most of the BA is deposited in landfills. The many landfills required are rapidly becoming an environmental burden (Chusilp et al., 2009a; Somna et al., 2012) (Fig. 2). In recent years, the use of agricultural and industrial by-products in concrete production has been the focus of a great deal of research because of the pozzolanic activity of ash materials, including the ash derived from combustion of sugarcane solid wastes (Villar-Cociña et al., 2008).

BA may be classified as a probable pozzolanic material, with the main factors affecting reactivity being the crystallinity of the silica present in the ash and the presence of impurities such as carbon and unburned material (Martirena et al., 1998). Good pozzolanic properties are obtained in BA heated between 800 and 1000 °C for 20 min (Villar-Cociña et al., 2008) or treated by air calcination at 600 °C for 3 h. The improved pozzolanic properties are due to the presence of amorphous silica, low carbon content, and high specific surface area (Cordeiro et al., 2009). Cordeiro et al. (2004) demonstrated that the pozzolanic activity of BA may be significantly increased by mechanical grinding in a vibratory mill. Ground BA with a loss-on-ignition of less than 10% provided an excellent pozzolanic material and could be used to partially replace Portland cement in concrete (Chusilp et al., 2009b). Many researchers have reported that BA exhibits satisfactory behavior in blended cementitious materials in concrete and has great potential for use in other applications (Alavéz-Ramírez et al., 2012). Singh et al. (2000) noted that the addition of 10% BA increased the compressive strength of cement paste at all ages of hydration. The chemical deterioration of blended cement is also reduced due to the pozzolanic nature of BA and the reduced permeability of BA-containing mixtures.
Replacement of fine aggregate with up to 20% BA resulted in equivalent or higher compressive strength and reduced water permeability and chloride diffusion (Ganesan et al., 2007; Chusilp et al., 2009a; Amin, 2011). Cordeiro et al. (2008) reported that the functional requirements of fresh SCC are different from those of vibrated fresh concrete. For instance, the RILEM technical committee (RILEM Technical Committee, 2006) stated that fresh SCC must possess the key properties of: (i) filling ability, (ii) passing ability, and (iii) resistance to segregation. The use of supplementary cementitious materials in SCC could reduce material costs while enhancing the self-compacting ability. Recent developments in SCC research are centered on the addition of supplementary cementitious materials with the objective of reducing solid waste disposal problems. Substantial energy and cost savings are possible when industrial by-products such as BA and LS are used in concrete production.

Limestone powder (LS) is commonly used as a secondary raw material in SCC formulation (Domone, 2008). This material is a by-product of stone crushing operations and normally presents a serious problem in terms of disposal, pollution, and health hazards. Ground limestone is generally considered an inert filler; although addition of limestone improves the hydration rate of cement. Physico-chemical changes occurring during Portland cement hydration are accelerated by the presence of calcium carbonate (CaCO₃), which increases the hydration rates of tricalcium silicate (C₃S) and cement and the precipitation rate of calcium carbosilicate hydrate (Péra et al., 1999; Ye et al., 2007). Adding fillers can increase the densities of the paste matrix and the interfacial transition zone between the matrix and the aggregate, thereby improving concrete performance (Shuhua and Peiyu, 2010).

In SCC mixtures, limestone fillers are associated with a small particle size, which enhances the packing density and decreases the amount of water entrapped in the system. When large volumes of limestone filler were added to SCC mixtures, self-compacting properties were achieved at a lower water-to-cement ratio of Type 1 Portland cement mixed with CaCO₃. Moreover, the volume of the continuous phase of lubricating paste was increased. Paradoxically, SCC mixtures must possess both high fluidity and high segregation resistance (Yahia et al., 2005; Felekoglu, 2007; Esping, 2008). Using blends of LS and mineral admixtures such as fly ash, rice husk ash, blast furnace slag, or natural pozzolans improves the overall performance of SCC (De Weerdt et al., 2011; Makhloufi et al., 2012; Rizwan and Bier, 2012; Sua-iam and Makul, 2013).

With the increased production and utilization of concrete, as well as the rapidly increasing consumption of natural aggregates that constitute the bulk of concrete, it is important to consider the environmental impacts of this material. The use of recycled aggregates can play key roles in reducing landfill waste and conserving natural aggregates, with many environmental benefits. Previous studies have examined the possibility of using waste materials as natural aggregate replacements in concrete (Richardson et al., 2011; Bravo and de Brito, 2012; Marie and Quiassawi, 2012; Zhao et al., 2013). This work investigated the interaction between LS and BA when used as partial fine aggregate replacements in SCC mixtures. The workability (slump flow, J-ring flow, and V-funnel flow) and hardened properties (compressive

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strength and ultrasonic pulse velocity) of several mixtures were measured. The use of as-received BA eliminated the cost and energy consumptions associated with grinding and increased the feasibility of using BA in concrete production.

### 2. Materials and methods

#### 2.1. Materials

Type 1 Portland cement (OPC) complying with ASTM C150 (American Society for Testing and Materials, 2009) was used in all compositions. BA was obtained from a sugar plant in the Singburi province of Thailand. Ash that had originally been dumped in an open area was collected, dried, and homogenized. LS was obtained from an industrial rock crushing plant located in Saraburi province, Thailand. The chemical compositions and physical properties of the cement, as-received BA, and LS are listed in Table 1. The mineralogical compositions of the BA and LS were determined using X-ray diffraction (Fig. 3). The major phases were quartz in BA and calcite in LS. The surface characteristics of the materials were examined using a Scanning Electron Microscope (SEM), and images obtained at approximately 1000× magnification are provided in Fig. 4.

A polycarboxylic ether-based high range water reducing admixture (HRWR) conforming to ASTM C494 (American Society for Testing and Materials, 2011a) standard type F with a specific gravity of 1.05 and a solid content of 42% was also used in the mixtures. The particle size distributions of the OPC, BA, and LS were measured using a Malvern Instruments Mastersizer 2000 particle size analyzer. The average particle size of the LS was slightly smaller than that of the OPC (Fig. 5), whereas the BA particles were substantially larger (Fig. 6). A continuously graded coarse aggregate with a specific gravity of 2.76 and a water absorption of 1.52% was used in all mixtures. The fine aggregate was river sand with a specific gravity of 2.67 and a water absorption of 0.71%. The aggregate materials were graded using sieve analysis (American Society for Testing and Materials, 2011b).

#### 2.2. Mixture proportions

The compositions of the SCC mixtures are presented in Table 2. Mixtures were prepared containing various fine aggregate compositions. The OPC and coarse aggregate contents were maintained at 550 kg/m³ and 708 kg/m³, respectively, in all mixtures. BA and LS were used to replace the river sand in amounts of 0, 10, 20, 40, 60, or 100% by volume. The water-to-cement (w/c) ratio was minimized by adding HRWR at a concentration of 2.0% by weight of cement, to provide the desired fluidity. The various SCC mixtures were identified using notations of the form Bax, Lsy, and BaxLSy in which x and y are the volume percentages of river sand replaced with BA and LS.

#### 2.3. Test methods

A 35-liter batch of each mixture was prepared using a tilting mixer. The addition sequence included sand, coarse aggregate, BA, and OPC. Effective mixing was critical to concrete performance. The addition of superplasticizer was delayed until 1–2 min after the addition of water, resulting in a higher fluidity mixture (Liu, 2011). The procedure is illustrated in Fig. 7.

The mixture was adjusted to maintain a slump flow diameter of 70 ± 2.5 cm. The unit weight of the freshly-prepared SCC was measured as specified in ASTM C138 (American Society for Testing and Materials, 2011c). The slump flow, T50cm flow time, J-ring flow, and V-funnel flow test procedures are illustrated in Figs. 8–10.

The maximum deformability of the concrete was evaluated using slump flow testing, which measures the time required for the

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### Table 1

Chemical composition and physical properties of Type 1 Portland cement (OPC), bagasse ash (BA) and limestone powder (LS).

<table>
<thead>
<tr>
<th>Chemical composition (% by mass)</th>
<th>Type 1 Portland cement (OPC)</th>
<th>Bagasse ash (BA)</th>
<th>Limestone powder (LS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide (SiO₂)</td>
<td>16.39</td>
<td>65.26</td>
<td>8.97</td>
</tr>
<tr>
<td>Aluminum oxide (Al₂O₃)</td>
<td>3.85</td>
<td>6.91</td>
<td>1.02</td>
</tr>
<tr>
<td>Ferric oxide (Fe₂O₃)</td>
<td>3.48</td>
<td>3.65</td>
<td>0.37</td>
</tr>
<tr>
<td>Magnesium oxide (MgO)</td>
<td>0.64</td>
<td>1.10</td>
<td>2.38</td>
</tr>
<tr>
<td>Calcium oxide (CaO)</td>
<td>68.48</td>
<td>4.01</td>
<td>46.77</td>
</tr>
<tr>
<td>Sodium oxide (Na₂O)</td>
<td>0.06</td>
<td>0.33</td>
<td>0.02</td>
</tr>
<tr>
<td>Potassium oxide (K₂O)</td>
<td>0.52</td>
<td>1.99</td>
<td>0.13</td>
</tr>
<tr>
<td>Sodium oxide (SO₃)</td>
<td>4.00</td>
<td>0.21</td>
<td>0.33</td>
</tr>
<tr>
<td>SiO₂ + Al₂O₃ + Fe₂O₃</td>
<td>23.72</td>
<td>75.82</td>
<td>10.36</td>
</tr>
</tbody>
</table>

### Physical properties

| Loss on Ignition (% by mass)     | 1.70                         | 15.34            | 39.54                 |
| Particle size distribution, D₉₀ (µm) | 23.32                       | 107.9            | 15.63                 |
| Specific gravity                 | 3.20                         | 2.35             | 2.76                  |
| Specific surface area (cm²/g)    | 610                          | 274              | 1300                  |

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uncompacted concrete to reach a spread of 50 cm from the time an inverted mould is first raised. This measurement provides a relative indication of the confined flow rate of the concrete mixture and was performed in accordance with ASTM C1611 (American Society for Testing and Materials, 2011d). The reported spread diameters are the averages of four measurements.

The passing ability was tested using a J-ring apparatus according to the procedure in ASTM C1621 (American Society for Testing and Materials, 2011e). The difference between the slump flow and J-ring flow is an indicator of the passing ability of the concrete.

The filling ability and deformability rate of the concrete mixtures when flowing through restricted areas were tested using a V-funnel. A V-shaped funnel was filled with fresh concrete and the time taken for the concrete to flow out of the funnel was measured and recorded as the V-funnel flow time, according to the procedure outlined in the EFNARC standards (EFNARC, 2002).

The typical workability acceptance criteria for self-compacting concrete mixtures are listed in Table 3.

The hardened properties were determined using ultrasonic pulse velocity (UPV) and compressive strength tests. Triplicate test specimens were prepared in the form of 150 mm diameter × 300 mm tall cylinders without compaction. The
specimens were initially covered with a plastic sheet. Specimens were removed from the moulds after 24 h and immersed in lime-saturated water until testing at 3, 7, 28, and 91 days, in accordance with ASTM C597 (American Society for Testing and Materials, 2011b) and ASTM C39 (American Society for Testing and Materials, 2011a).

3. Results

3.1. Properties of fresh SCC

3.1.1. Water requirement

The SCC w/c ratios producing controlled slumps of 70 ± 2.5 cm in diameter are plotted in Fig. 11. Mixtures containing BA required more water than those containing only LS or mixtures of BA and LS. The water requirement increased with increasing amounts of BA mostly due to the porous nature of the particles and their greater surface area, both of which enhance the absorption of water (Chusilp et al., 2009b). The water requirements of mixtures containing both BA and LS were substantially reduced. Some of the physical effects were associated with the small size of the limestone particles, which enhances the packing density and reduces the interstitial void fraction and therefore decreases the amount of water trapped in the system (Yahia et al., 2005).

3.1.2. Unit weight

The unit weights of SCC mixtures are plotted in Fig. 12. The unit weight decreased with increasing BA content and increased with increasing LS content. When BA was combined with LS, the unit weights of SCC mixtures were decreased, and the unit weight was more influenced by the BA than by the LS content. In other words, the unit weights of SCC mixtures containing LS and BA were higher than those of the SCC mixtures mixed with BA alone, but lower than those of SCC mixtures mixed with LS alone. The lower unit weight of mixtures containing BA is due to an increase in porosity and the higher unit weight of LS mixtures is due to the greater density of the LS particles (2.76 vs. 2.67 for river sand and 2.35 for BA) (Akram et al., 2009; Sua-iam and Makul, 2013).

3.1.3. T50cm slump flow

The slump flow diameter of the SCC mixtures was maintained at an average of 70 ± 2.5 cm, which is an indication of good workability. Slump flow time testing is the simplest and most commonly adopted test method for evaluating the flowability of self-compacting concrete. The standard test method is described in ASTM C1611 (American Society for Testing and Materials, 2011d). The time required for the SCC mixtures to reach 50 cm ranged from 3 to 7 s, in accordance with EFNARC guidelines (EFNARC, 2002) (Table 3). The slump flow time increased monotonically with increasing aggregate replacement in mixtures containing both BA and LS. The slump flow time was between 4 and 6 s in mixtures containing only BA, 6–20 s in mixtures containing only LS, and 4–9 s in mixtures containing both constituents (Fig. 13). Maximum slump flow times occurred in mixtures containing 20% BA or 60% LS. The higher slump flow times at these concentrations may have been due to increased surface area in the case of BA-containing mixtures and improved packing in LS-containing mixtures (Felekoglu, 2007). The decreased flow times in mixtures containing larger amounts of BA or LS may have been due to the increased water requirement, which resulted in weaker cohesion and interlocking between the river sand, BA, and LS particles (Sua-iam and Makul, 2013).

3.1.4. V-funnel test

The V-funnel test measures the effects of both internal and external friction within a gradually reducing funnel section. In this test particle shape becomes a very important flow parameter (Rizwan and Bier, 2012). V-funnel flow times are specified in the EFNARC guidelines to be 8–12 s (EFNARC, 2002) (Table 3). The passing time increased in proportion to the water requirement and fine aggregate replacement level. In mixtures BA10, LS10, and LS20, the V-funnel times were within the specified range. The flow time increased with increasing amounts of BA because the particles absorbed water, resulting in highly viscous mixtures and leading to segregation of the fine aggregate. The flow time decreased with increasing LS content by more than 60% due to the lack of cohesiveness and increased unit weight.

SCC mixtures displayed acceptable V-funnel performance when they contained both BA and LS in a 1:1 ratio at replacement levels of not more than 40% (Fig. 14).

3.1.5. J-ring test and blocking assessment

Characteristics such as passing ability and segregation resistance are normally investigated using the J-ring test. Once the test cone is lifted, the mixture is allowed to flow through a network of

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Table 2

Compositions of SCC mixtures.

<table>
<thead>
<tr>
<th>No. of Mixture codes</th>
<th>Fine aggregate</th>
<th>Bagasse ash (BA) and Limestone powder (LS)</th>
<th>Type 1 Portland cement (OPC)</th>
<th>Coarse aggregate</th>
<th>Water</th>
<th>Superplasticizer</th>
<th>HRWR (%by weight of cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Control</td>
<td>OPC</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>813</td>
<td>0</td>
<td>708</td>
</tr>
<tr>
<td>2 BA10</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>731</td>
<td>0</td>
<td>708</td>
</tr>
<tr>
<td>3 BA20</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>650</td>
<td>144</td>
<td>708</td>
</tr>
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<td>4 BA40</td>
<td>Mixture</td>
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<td></td>
<td>Fine aggregate</td>
<td>531</td>
<td>288</td>
<td>708</td>
</tr>
<tr>
<td>5 BA60</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>325</td>
<td>432</td>
<td>708</td>
</tr>
<tr>
<td>6 BA80</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>163</td>
<td>577</td>
<td>708</td>
</tr>
<tr>
<td>7 BA100</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>721</td>
<td>0</td>
<td>708</td>
</tr>
<tr>
<td>8 LS10</td>
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<td></td>
<td>Fine aggregate</td>
<td>731</td>
<td>0</td>
<td>851</td>
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<tr>
<td>9 LS20</td>
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<td>Fine aggregate</td>
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<td>0</td>
<td>169</td>
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<tr>
<td>10 LS40</td>
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<td></td>
<td>Fine aggregate</td>
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<td>0</td>
<td>339</td>
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<tr>
<td>11 LS60</td>
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<td></td>
<td>Fine aggregate</td>
<td>325</td>
<td>0</td>
<td>508</td>
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<tr>
<td>12 LS80</td>
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<td>677</td>
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<td>Fine aggregate</td>
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<td>0</td>
<td>846</td>
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<tr>
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<td></td>
<td>Fine aggregate</td>
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<td>36</td>
<td>42</td>
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<tr>
<td>15 BA10LS10</td>
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<td></td>
<td>Fine aggregate</td>
<td>650</td>
<td>72</td>
<td>85</td>
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<td>488</td>
<td>144</td>
<td>169</td>
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<td>17 BA30LS30</td>
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<td></td>
<td>Fine aggregate</td>
<td>325</td>
<td>216</td>
<td>254</td>
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<tr>
<td>18 BA40LS40</td>
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<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>163</td>
<td>288</td>
<td>339</td>
</tr>
<tr>
<td>19 BA50LS50</td>
<td>Mixture</td>
<td>550</td>
<td></td>
<td>Fine aggregate</td>
<td>–</td>
<td>360</td>
<td>423</td>
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reinforcements. The differences between the slump flow and J-ring flow diameters are used to obtain the blocking assessment according to the criteria described in Table 3 and adapted from ASTM C1621 (American Society for Testing and Materials, 2011e), in which a difference of 0–25 mm is defined as no visible blocking, 25–50 mm is defined as minimal to noticeable blocking, and greater than 50 mm is defined as noticeable to extreme blocking.

Less than 50 mm of blocking was observed in samples containing less than 40% BA or LS alone and up to 60% of a combination of BA and LS (Fig. 15). Mixtures containing a combination of BA and LS achieved adequate passing ability and maintained sufficient resistance to segregation around congested reinforcement areas due to the combined influence of a decrease in BA content and an increase in water-to-cement ratio. Decreasing the amount of river sand by replacement with the finer-grained LS could lead to increased viscosity and hence result in lower segregation during and after concrete placement (Khayat, 1999).

3.2. Properties of hardened SCC

The compressive strength and ultrasonic velocity of the mixtures were tested at 3, 7, 28 and 91 days. Reported values are the means of tests performed on three specimens.

3.2.1. Compressive strength

The average compressive strengths of the SCC samples at each age are plotted in Fig. 16. The compressive strength continued to increase over the 91-day curing period. The control SCC mixture...
had a compressive strength of 65.0 MPa at 28 days, which increased to 82.8 MPa after 91 days. Addition of increasing amounts of BA generally decreased the strength at a given age due to the greater porosity of the material (Rukzon and Chindaprasirt, 2012) as indicated by the higher water requirement (Chusilp et al., 2009b; Akram et al., 2009). The compressive strength of the mixture containing 100% BA was not measured due to failure of the concrete to set as a result of the high water content required to maintain slump flow. The greatest compressive strength was achieved when the mixture contained a 10% fine aggregate replacement of LS. Improvement stemmed from the void-filling ability of the smaller particles and was more pronounced at lower w/c ratios (De Weerdt et al., 2011). The main constituent of LS is CaCO3 which has an accelerating effect on C3S and cement hydration and leads to the precipitation of calcium carboaluminate hydrate, which may also contribute to void filling (Péra et al., 1999; Esping, 2008; Shuhua and Peiyu, 2010; Makhloufi et al., 2012; Sua-iam and Makul, 2013).

3.2.2. Ultrasonic pulse velocity
The average UPV results at 3, 7, 28, and 91 days are illustrated in Fig. 17. The trends in UPV and compressive strength in these experiments were similar. UPV increased with increasing compressive strength for all mixtures. The UPV of the control SCC mixture was 6048 km/h at 28 days, which increased to 18,720 km/h after 91 days. The variations correspond to the degree of densification within the internal structure, and higher velocities generally indicated a better quality SCC mixture. Addition of increasing amounts of BA decreased the ultrasonic pulse velocity due to the increased porosity in the hardened concrete (Rukzon and Chindaprasirt, 2012). The initially high porosity was reduced during curing due to the pozzolanic activity of BA, which produces calcium silicate hydrates (C–S–H) belonging to be tobermorite family (Villar-Cocitha et al., 2008). Addition of LS increased the ultrasonic pulse velocity by decreasing the total porosity due to the filling effect of the fine LS as well as a chemical effect in which the calcium carbonate of the LS interacts with the aluminurate hydrates formed during OPC hydration, leading to the stabilization of the ettringite phase and resulting in an increase in the total volume of the hydration products (Ye et al., 2007; De Weerdt et al., 2011; Makhloufi et al., 2012).

3.2.3. Relationship between compressive strength and ultrasonic pulse velocity
The relationships between the compressive strength and the UPV of the SCC mixtures are described in Fig. 18. The UPV increased with increasing compressive strength for all mixtures. Good correlations were obtained between compressive strength and UPV, regardless of the fine aggregate composition. The relationship between the two properties was described by the equation $CS = 3.2623e^{0.0020UPV}$, in which CS and UPV represent compressive strength and ultrasonic pulse velocity, respectively. The correlation

<table>
<thead>
<tr>
<th>Workability test</th>
<th>Slump flow (mm)</th>
<th>$T_{50\text{cm}}$ (sec)</th>
<th>V-funnel (sec)</th>
<th>Blocking assessment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>650–800</td>
<td>3–7</td>
<td>8–12</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0–25</td>
</tr>
</tbody>
</table>

---

Table 3: General acceptance criteria for SCC mixtures according to ASTM and EFNARC standards.

Fig. 11. Required water-to-cement (w/c) ratios for SCC mixtures.

Fig. 12. Unit weight of SCC mixtures.

Fig. 13. Time required for mixtures to reach slump flow diameter of 50 cm.
The relationship between compressive strength and UPV for the individual compositions is presented in Fig. 19. The best-fit equation for BA-containing mixtures was $CS = 4.525e^{0.0002UPV}$, with a correlation coefficient ($R^2$) of 0.9089. For LS-containing mixtures, the best-fit equation was $CS = 2.5888e^{0.0002UPV}$, with a correlation coefficient ($R^2$) of 0.8107. For mixtures containing both BA and LS, the best-fit equation was $CS = 1.4672e^{2.6838UPV}$, with a correlation coefficient ($R^2$) of 0.9289.

4. Discussion

The use of LS with increasing amounts of BA waste in the production of SCC has advantages and disadvantages when compared...
to the use of SCC prepared with OPC alone. An important advantage is that the unit weight of SCC containing BA and LS is lower than that of the control SCC, which reduces the long-term repair and maintenance costs when this SCC is employed in practical concrete buildings.

One disadvantage is that SCC containing BA required high water content compared to the control SCC, according to the percentage of BA replacement in the fine aggregate. This high water content (and, thus, high w/c ratio) led to decreased compressive strength and density of the SCC, as illustrated by the UPV results. This effect could be compensated by mixing BA with LS. The LS powder acts as a filler to pack the internal structure, reduce the interstitial voids, and, consequently, enhance the density and strength of SCC. Moreover, high percentage replacement of BA in fine aggregate (>40% by volume) can lead to blocking when the SCC flows though obstructions, such as congested reinforcements, when compared to control SCC. To solve this problem, LS can be added to improve the flowability of SCC, allowing BA to be used as a fine aggregate replacement in amounts of up to 60% by volume.

The use of BA as a fine aggregate replacement required large amounts of water to achieve the desired slump flow diameter of 70 ± 2.5 cm and to meet the flowability requirements specified by EFNARC and others (EFNARC, 2002). The high water requirement was due to the large particle size and high surface area of the BA particles (Chusilp et al., 2009a,b). Addition of large amounts of water has negative effects on the properties of fresh concrete, leading to segregation, bleeding, and blockage when flowing through narrow spaces between reinforcements. In addition, the hardened SCC concrete mixed with BA was of lower strength, due to the increased capillary porosity and loss of interfacial adhesion between the cement paste and the aggregate (Khayat, 1999; Felekoglu, 2007).

On the other hand, the angularity, irregular shape, and high porosity of the BA particles resulted in increased friction between the cement particles and BA particles (Somna et al., 2012). The chemical reaction rate on the surface of the pozzolanic particles was slower than the diffusion rate of the reactants through the product layer formed around the nucleus. This may have been due to the high porosity of the reaction product layer in BA, which facilitates quick diffusion in pozzolanic/CH systems (Villar-Cociña et al., 2008). Addition of LS improved the workability of SCC (Fig. 20). LS is commonly used as a filler to improve the workability and stability of fresh concrete. When added to SCC mixtures, LS may fill voids and improve the particle arrangement in the system, ensuring better distribution of the mixing water to achieve adequate mixture fluidity, bind excess water, and increase the volume of the continuous phase of lubricating paste.

The SCC must simultaneously possess two disparate properties: high flowability and high segregation resistance (Yahia et al., 2005; Esping, 2008). Another possible reason for the difference in

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**Fig. 17.** Ultrasonic pulse velocities of hardened SCC mixtures.

**Fig. 18.** Relationship between compressive strength and ultrasonic pulse velocity.

**Fig. 19.** Relationship between compressive strength and ultrasonic pulse velocity when BA, LS, and BA/LS mixtures are considered separately.
relative flow times for mixtures containing BA and LS may be the improved packing obtained when using fine spherical particles (Felekoglu, 2007). However, close packing occurs at a critical LS content, and a substantial increase in viscosity is expected at greater concentrations of LS. The increase in viscosity and flow time beyond this critical limit may be explained by the increase in interparticle friction due to the increase in solid–solid contact (Yahia et al., 2005). Slump flow and V-funnel flow tests have been proposed for testing deformability and viscosity (American Concrete Institute, 2007). Reducing the w/c ratio can limit the deformability of the cement paste (Fig. 21). Increasing the w/c ratio can ensure high deformability, reduce the cohesiveness of the paste and mortar, and lead to the segregation of the fine and coarse aggregate particles, causing flow blockage. Therefore, decreases in the w/c ratio to enhance deformability must be accomplished without substantial reductions in cohesiveness (Khayat, 1999).

Felekoglu (2007) examined the relationship between the V-funnel time of fresh concrete mixtures and the surface pore concentration of the hardened concrete. When the viscosity of the mixture was extremely high, the pores in the concrete could not be collapsed and were trapped in the final concrete structure, leading to observable porosity on the mould surfaces of the concrete. When the viscosity was sufficiently low, the air bubbles escaped easily from the concrete surface, and an improved surface appearance was obtained.

The relationship between compressive strength and water-to-cement ratio of the SCC at 3, 7, 28, and 91 days is depicted in Fig. 22. The correlation coefficient ($R^2$) was above 0.94 for all curing times and mixtures. The compressive strength decreased with increasing w/c ratio and increased with increasing cure time. The need for a higher w/c ratio in BA-containing mixtures resulted in lower compressive strength (Chusilp et al., 2009a), although the slow pozzolanic reaction of the BA improved the compressive strength of concrete over long curing times. In suitable proportions pozzolanic secondary raw materials such as BA and LS can increase the strength through physical or chemical effects. Some of the physical enhancements are associated with the small size of the LS.

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particles, which can enhance the packing density of the powder and reduce the interstitial void volume, thus decreasing the amount of water entrapped in the system (Yahia et al., 2005). LS powders can chemically react with the aluminate phase of cement to produce calcium carboxaluminate. During the hydration of the silicate phases, small amounts of filler are incorporated into the C–S–H through the formation of carbonated hydrated calcium silicate. Addition of limestone filler supplies ions to the phase solution, thus modifying the kinetics of hydration and the morphology of the hydration products (Péra et al., 1999; Yahia et al., 2005; Felekoglu, 2007). The addition of limestone also reduces the compressive strength of concrete due to dilution of pozzolanic reactions (De Weerdt et al., 2011; Rizwan and Bier, 2012), affecting the durability of the finished concrete (Makhlouf et al., 2012).

5. Conclusions and future work
In the present study, increasingly high volumes of BA waste obtained from the sugar industry were used as fine aggregate replacement materials in the production of high-performance SCC, which was obtained by adding LS powder waste obtained from the stone-crushing industry. The goal was to maximize the amount of unprocessed or as-received BA content as a new fine aggregate. For the performance of SCC with controlled flowability conditions (slump flow diameter of 70 ± 2.5 cm), there were advantages to using BA and LS powder in the workability of the concrete. For instance, SCC mixtures containing LS and BA required lower w/c ratios than SCC containing only BA, leading to higher workability. However, some blocking occurred in mixtures containing 40% LS and 40% BA (“high-volume” BA content) during V-funnel and J-ring tests. The unit weight of the SCC decreased with increasing BA content and increased with increasing LS content, allowing a type of lightweight SCC to be obtained. The resulting concrete structure had a decreased weight and low long-term maintenance costs. In terms of the hardened properties of SCC combinations, BA and LS could be employed to decrease the w/c ratio by more than 24%. The compressive strength of SCCs comprised of BA and LS mixtures increased when lower w/c ratios were used, compared to SCCs mixed with BA alone. Incorporation of suitable levels of BA and LS improved the early-stage compressive strength development, due to filling effects and pozzolanic reactions. The optimal SCC, which contained 20% LS and 20% replacement of the fine aggregate by BA, showed improved properties compared to normal SCC and met the requirements of the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC) guidelines. To conform to the performance-based design of SCC, future studies should systematically investigate the effects of LS powder use on the durability of SCC incorporating large amounts of BA waste.

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