

Comparison of Setting Time Measured Using Ultrasonic Wave Propagation with Saw-Cutting Times on Pavements – A Case Study

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ABSTRACT

At present, there is little solid guidance available to assist contractors in choosing when to schedule saw cutting of joints in slabs on grade. Knowledge of when the sawing window opens and closes would help in reducing the risk of raveling or random cracking due to sawing too early or too late. The aim of this case study was to confirm that initial set can be measured using an ultrasonic pulse velocity (UPV) approach in the field, and to assess whether there was a relationship between initial set and sawing time for pavement concrete in the field. This case study summarizes 24 construction sites that were visited in Minnesota, Missouri, and Iowa over a two-year period. At each site, initial set was determined using a p-wave propagation technique with a commercial device using samples of concrete collected in front of the paver and tested next to the pavement. Calorimetric data were collected using a commercial semi-adiabatic device on the majority of the sites.

Keywords: ultrasonic pulse velocity; p-wave; pavement saw-cutting; calorimetry; setting time

INTRODUCTION

The primary purpose of joints in slipform concrete pavement is to control random cracking. A weakened plane can be introduced to ensure cracking occurs in a controlled manner at specific locations. Several methods can be used to induce joints in early age concrete, including saw-cutting, hand-tooling and installation of preformed strips (Raoufi et al. 2009). Saw-cutting is considered as the most practical way to induce joints for slipform paving operations.

At present, there is little solid guidance regarding the ideal time the saw-cut should be installed in slabs. The American Concrete Institute (ACI Committee 224 1995) recommended that “the joints should be sawed as soon as practical wherein the concrete should have hardened enough”. Indiana DOT specification 503.03 (1999) specified 2 to 12 hours as the saw-cutting window for transverse

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joints and “sufficiently hardened” for longitudinal joints. Too early and there is a risk of raveling and spalling, but too late and there is a risk of random cracking. Failures may lead to disputes between agency and contractor as to who is responsible and what remedial action should be taken, leading to unexpected costs to both parties (Taylor and Wang 2015). There are, therefore, financial benefits to better predicting saw cutting times. Fewer slabs will need to be replaced or patched due to failures like random cracking, while the overtime costs can be reduced because the sawing crew will not need to wait around until the slab is ready.

Therefore, it is useful for contractors to know when a concrete mixture reaches initial set, or when the sawing window will open. This work was based on the hypothesis that measuring the set time of concrete can be tied to saw-cutting timing, and as an added benefit may help assess uniformity between concrete batches.

The aim of this case study was to confirm that initial set can be measured using an ultrasonic pulse velocity (UPV) approach in the field, and to assess whether there was a relationship between initial set and sawing time for pavement concrete in the field.

BACKGROUND

The sawing window, also known as the “green zone”, describes the period during which the sawing operation should be conducted to prevent raveling (too early) and random cracking (too late). It generally starts well before the temperature reaches the peak during hydration process and end around the time of the temperature peak. The rate of hydration governs the sawing window as well as other factors such as drying conditions and hardness of the coarse aggregate. The initial set is influenced by similar factors including cementitious chemistry and system temperature (Taylor and Wang 2015).

Sawing can be conducted using conventional or early entry saws. The conventional saw generally performs a wet cut, i.e., water is used to cool the blade. It should be operated at about 2.4-3.0 meter per minute to ensure the most economical cutting speed based on labor, blade and operation costs (Raoufi et al. 2009). Conventional sawing is also a “down-cut” operation which drives slurry out behind the blade.

Early entry sawing was first introduced in 1988 and it is a dry “up-cut” process using lighter machines. Cuts also tend to be shallower. A spring loaded skip plate straddles the blade to hold concrete in place, meaning that sawing can be conducted earlier than conventional sawing. The “up-cutting” reduces slurry in the joint (Raoufi et al. 2009).

Typical conventional and early entry saws are shown in Figures 1 and 2.



Figure 1. A typical early entry saw-cutting machine



Figure 2. A typical conventional saw-cutting machine

Approaches determining the “right” time to conduct sawing on a fresh-paved concrete slab tend to be subjective. The most commonly used method for saw crews is to scratch the slab surface with a penknife, or to stand on the slab to observe footprint depth. An alternative is to try a cut and observe the degree of raveling. However, a very clean cut may indicate that it is too late and that the risk of random cracks ruining in front of the baled is high. Other researchers have established several approaches to predict the sawing window, including calorimetry, finite element modeling, HIPERPAV software, maturity meter, penetration resistance and UPV methods. Their features, advantages and challenges are summarized in Table 1. Selected methods, including calorimetry, penetration resistance and UPV were assessed in this case study.

Table 1. Summary of existing sawing prediction methods

Methods	Features	Advantages	Challenges	References
Calorimetry	Featured points on hydration history used to predict setting time. Can be used for early-age strength prediction in situ.	Portable and easy to use. Effective to determine incompatibility and infer physical properties.	Lack of guidelines to interpolate hydration temperature with concrete performance.	Wang et al. 2015; Sandberg and Liberman 2007; Taylor et al. 2006

Empirical	Inspect joints: raveling or clean cut. Penknife scratch or stand on the slab to observe footprint depth.	Most commonly used method in situ. Easy and fast inspection.	Highly empirical and subjective.	Taylor and Wang 2014
Finite element software	Fractured-based finite element software programs.	Model prediction on saw cut time and depth. Reported as a promising approach.	Finite element model is complicated to develop and cannot be widely used for contractors.	Raoufi et al. 2009
HIPERPAV Software	Computer software as a planning tool associated with numerous models based on the temperature prediction model.	Provide an indirect determination of the end of the sawing window. User friendly.	No significant correlation with actual pavement temperature at early-age. Need further calibration on temperature prediction models.	HIPERPAV 2004; McCullough 1999
Maturity and strength	Mathematical function to provide evidences on strength needed to conduct sawing.	The Arrhenius function seems to work better and hyperbolic strength-maturity relationship can be used.	Arrhenius function: complicated. Nurse-Saul function: simple but not accurate over a wide range of temperatures at early age. Without considerations of aggregate strength effects.	Raoufi et al. 2009; Barde et al. 2004
Penetration resistance	Standard test to measure setting time. Penetration resistance of sieved mortar.	Check uniformity between mixtures. Can be used in both lab and field conditions.	No considerations of aggregate strength effects on sawing. Time consuming and definitions of initial and final set seem to be arbitrary.	Wang et al. 2015; ASTM C403 2008
UPV	Wave propagation method tells the pulse velocity history when traveling through fresh concrete.	Portable and easy to use on site. Featured points on UPV curve correlate well with initial set time.	Contradictory conclusions may be drawn from previous research on featured points of UPV curve.	Wang et al. 2015; Taylor and Wang 2015; Taylor and Wang 2014

Ultrasonic pulse velocity (UPV)

A previous study has discussed the theoretical background of this method is that the speed of sound is slower in a fluid than in a solid (Taylor and Wang 2014). The velocity of sound can be determined using a device that tracks the time for a signal to travel through a sample with a known depth. Waves normally used in this application are compression (p-waves) that travel through the material, and shear (s-waves) that travel at the interface between the material and its container or air (Wang et al. 2015). Because p-waves are less sensitive to sample transducer contact issues than s-waves, they allow a more accurate determination of the velocity through a composite material, such as concrete, while delivering high signal-to-noise ratio (Robeyst et al. 2008). According to Biot's (1956) theory, the velocity of sound in a continuous medium is a function of elastic modulus, density and Poisson's ratio.

Taylor and Wang (2014) indicated that it is reasonable to assume that the start of the sawing window can be correlated with the initial set which measured by UPV method because both are affected by the same factors, such as:

- Chemistry of the mixture: increasing alkali content tends to accelerate hydration
- SCM type and dose: SCMs generally slow hydration
- Temperature: increasing mixture temperature accelerates hydration

Previously-reported work clearly showed a relationship between concrete initial set time determined by penetration resistance and using the UPV device (Wang et al. 2015). This case study aimed at determining whether correlation exists between setting times measured in the field by UPV method and the sawing times on the same slabs.

Penetration resistance test

In ASTM C403 (2008), initial and final setting times are defined as the times required for sieved mortar from concrete to reach 3.5 MPa and 27.6 MPa of resistance to penetration of a cylindrical probe.

Calorimetry

Calorimetry is the measurement of heat lost or gained from a sample in a chemical reaction, such as cement hydration. It can be used to assess the uniformity and compatibility in mixtures due to the effect of SCMs and chemical additives on hydration kinetics. The temperature-time curve can reflect hydration related properties, such as setting, stiffening and maturity (Sandberg and Liberman 2007; Wang et al. 2006; Sandberg and Roberts 2005; Bensted 1987; Lerch 1946).

Sandberg and Liberman (2007) found that the hydration time at which a given “fraction” of the hydration temperature rise occurs can be used to assess thermal setting time, i.e., 20% and 50% fractions can be correlated with initial and final thermal setting times. However, there are somehow arbitrary, especially for final setting times which in turn is based on an arbitrarily selected penetrometer reading of 27.6 MPa.

Correlation between the penetration resistance in accordance with ASTM C403, calorimetry data and UPV approaches is reasonable for initial set, as shown in a typical set for a single lab mix (Figure 3). Initial sets determined using these approaches are based on the times reach penetration resistance of 3.5 MPa, 20% of calorimetry temperature rise and when pulse velocity starts to increase, respectively.

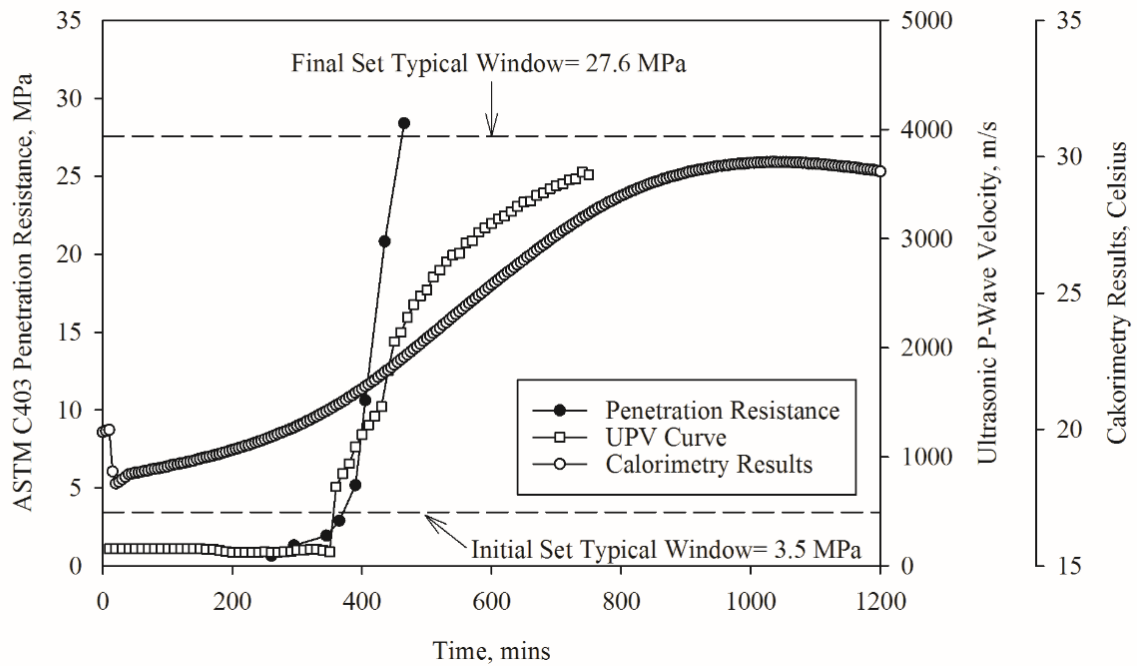


Figure 3. Plots from different measurement approaches for a lab mix

WORK CONDUCTED

Sites where tests were conducted in the field are summarized in Table 2. 24 pavement construction sites were visited over a three-year period from 2013 to 2015, including 10 early entry saw-cutting sites in Iowa and Minnesota and 14 conventional saw-cutting sites in Minnesota and Missouri.

At each site, paving start times were recorded. Concrete was taken at the front of paver and three 100 by 200 mm cylindrical molds were cast, one for UPV measurement and the other two for the semi-adiabatic calorimetry test. Mortar was sieved through a 4.75 mm screen for initial set times determination in accordance with ASTM C403. Sawing started at crews' judgement and the elapsed time was recorded.

A commercial semi-adiabatic calorimeter was used to monitor the temperature changes of concrete samples on a majority of sites (Figure 4). Data were collected up to 24 hours.



Figure 4. Calorimetry test device for heat of hydration of concrete (Taylor and Wang 2015)

A commercial UPV device was used to track pulse velocity of field concrete samples (Figure 5). It was composed of an integrated waveform display, two longitudinal wave transducers with a frequency of 54 kHz and a plexiglass rod with a known velocity for calibration. The top transducer was set on a plexiglass sheet sized to fit inside the cylindrical mold. The bottom transducer was set in contact with the bottom of the mold. A gel couplant was applied between the transducer and their contact surfaces to reduce attenuation of the wave at the interfaces. Test sample was placed next to the pavement slab so that it was exposed to the same environmental condition.



Figure 5. Test setup with sample and transducers in a wooden frame for stability (Taylor and Wang 2015)

Table 2. Site details

Site ID	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	Site MO	Site I	Site J	Site K
Date	7/17/14	7/18/14	7/22/14	7/21/14	8/14/14	8/15/14	8/29/14	9/12/14	8/27/14	9/26/14	6/1/15	7/30/15
Cement, kg/m ³	237	237	325	237	237	237	237	237	231	279	237	237
Fly Ash, kg/m ³	101	104	81	101	101	95	101	102	77	47	101	113
Water, kg/m ³	135	125	154	128	125	113	125	122	126	121	128	136
Sand, kg/m ³	745	722	739	833	758	698	645	443	753	684	814	635
Coarse Sand, kg/m ³	-	-	-	-	-	-	240	332	-	-	-	-
Coarse Agg., kg/m ³	1071	926	980	978	1091	811	959	1071	829	952	705	1179
Intermediate Agg., kg/m ³	-	-	-	-	-	377	-	-	301	224	290	-
Aggregate Type	Limestone	Limestone	Limestone	Quartzite	Granite	Gravel	Gravel	Gravel	Limestone	Gravel	Granite	Gravel
Air Entraining Agent	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Water Reducer	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	WRDA 82	Type A	Type A	Type A
Location	City	Interstate	City	County	City	Highway	Highway	Interstate	Highway	Interstate	County	Interstate
Pavement Type	Reconstruction	Unbonded overlay	Reconstruction	Bonded overlay	Bonded overlay	Overlay using fabric	-	Unbonded overlay	New pavement	Reconstruction	Unbonded overlay	Unbonded overlay
Thickness (cm)	22.9	24.1	22.9	12.7	10.2	15.2	-	20.3	30.5	27.9	12.7	22.9
Joint Spacing (m)	4.6	4.6	4.6	1.8	1.8	3.7	-	4.6	-	4.6	1.8	4.6
Saw Type	Early entry	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
Average temp. °C	19	21	23	26	18	22	23	9	28	21	22	22

Table 2. Sites information (Continuous)

Site ID	Site L	Site M	Site N	Site O	Site P	Site Q	Site R	Site S	Site T	Site U	Site V	Site W
Date	7/31/15	8/5/15	8/6/15	8/27/15	5/24/2013	6/18/2013	8/7/2013	8/19/2013	8/26/2013	10/2/2013	10/15/2013	10/18/2013
Cement, kg/m ³	240	237	237	237	266	266	262	266	262	267	-	271
Fly Ash, kg/m ³	101	101	101	107	66	66	65	66	65	67	-	68
Water, kg/m ³	130	124	135	131	133	133	134	133	134	133	-	146
Sand, kg/m ³	698	668	686	756	750	750	866	777	998	755	-	819
Coarse Sand, kg/m ³	-	-	-	-	-	-	-	-	-	-	-	-
Coarse Agg., kg/m ³	1138	1187	1121	1082	828	828	713	804	833	820	-	1007
Inter Agg., kg/m ³	-	-	-	-	279	279	281	280	-	210	-	-
Aggregate Type	Limestone	Gravel	Gravel	Limestone	Limestone	Limestone	Quartzite	Limestone	Limestone	Limestone	-	Limestone
Air Entraining Agent	Yes	Yes	Yes	Yes	Brett	Brett	Yes	MBAE	Brett	Brett	-	BASF
Water Reducer	Type A	Type A	Type A	Type A	Brett	Brett	Type A	Pozzoloth	Brett	Brett	-	BASF
Location	County	Interstate	Interstate	Interstate	Highway	County	Interstate	Interstate	Interstate	Interstate	City	City
Pavement Type	Unbonded overlay	Unbonded overlay	New pavement	Reconstruction	Reconstruction	New pavement	Unbonded Overlay	Reconstruction	Reconstruction	Reconstruction	Reconstruction	Reconstruction
Thickness (cm)	15.2	24.1	20.3	27.9	-	-	-	-	-	-	-	-
Joint Spacing (m)	1.8	4.6	4.6	4.6	-	-	-	-	-	-	-	-
Saw Type	Early entry	Conv.	Conv.	Conv.	Early entry	Early entry	Early entry	Early entry	Early entry	Early entry	Early entry	Early entry
Average temp. °C	22	23	24	18	17	29	23	27	31	24	9	8

RESULTS AND DISCUSSION

Test results are summarized in Table 3. Sample batch times vary from 7:45 am to 14:03 pm. Average ambient temperature ranged between 8 and 31 °C. Initial set times determined by calorimetry fraction, UPV and penetration resistance approaches for selected sites are recorded.

Table 3. Recorded test results for each site

Site ID	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	Site I	Site MO	Site J	Site K
Sample batch time	9:05	9:45	9:00	9:30	9:30	8:55	9:30	10:00	8:45	8:38	9:35	8:45
Initial set (calorimetry), min	350	300	320	245	320	260	-	200	245	-	380	205
Initial set (UPV), min	350	225	225	160	300	295	340	480	255	162	265	345
Sawing time, min	540	670	520	465	600	540	700	870	630	485	575	740
Average temp. °C	19	21	23	26	18	22	23	9	28	21	22	22
Site ID	Site L	Site M	Site N	Site O	Site P	Site Q	Site R	Site S	Site T	Site U	Site V	Site W
Sample batch time	8:40	9:00	9:00	9:30	7:45	11:15	8:15	14:03	8:00	9:20	9:20	12:30
Initial set (ASTM C403), min	-	-	-	-	290	153	285	184	255	209	441	316
Initial set (calorimetry), min	295	170	130	365	-	-	390	180	228	230	300	330
Initial set (UPV), min	240	170	230	260	276	135	270	195	260	220	400	295
Sawing time, min	455	460	615	660	480	330	460	450	455	470	625	1050
Average temp. °C	22	23	24	18	17	29	23	27	31	24	9	8

The correlations among initial set measurement approaches are shown in Figure 6. Good correlation can be observed between initial set times measured by penetration resistance and UPV methods, while there is a weak correlation between the times measured by penetration resistance and calorimetry fraction approaches. It is likely because the semi-adiabatic nature of calorimetry cannot simulate the concrete under field conditions. Ambient environment, such as temperature,

humidity and wind speed, may have a strong effect on concrete setting behavior. As shown in Figure 7, high ambient temperature seems to shorten the elapsed time of saw cut for both conventional and early entry saw at different rates.

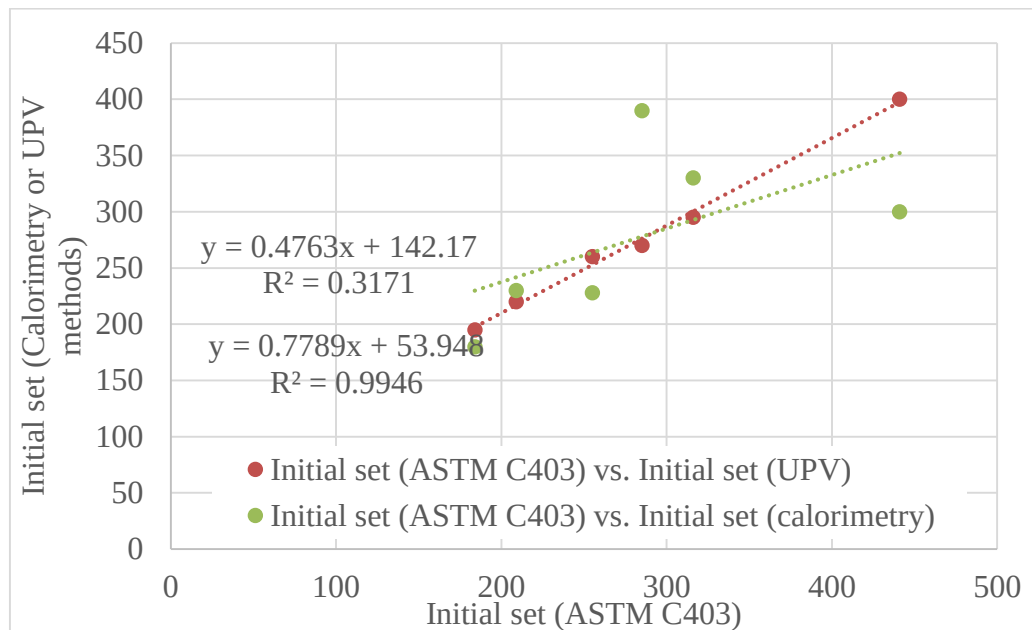


Figure 6. Correlations among initial set measurement approaches

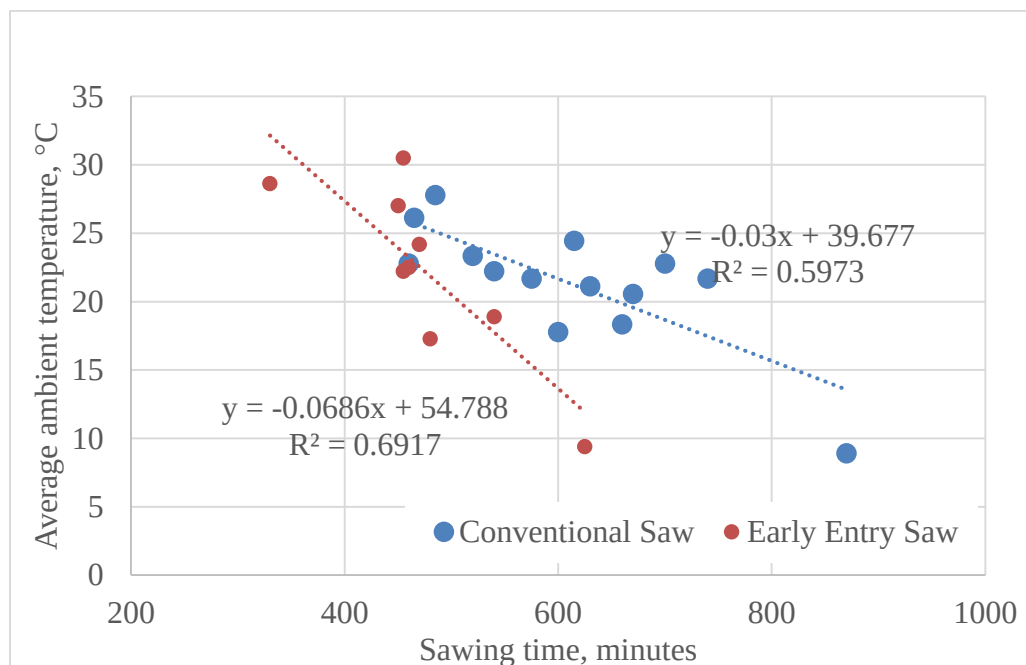


Figure 7. The relationship between average ambient temperature and sawing time (Taylor and Wang 2015)

There appears to be a good correlation between sawing and setting times for early entry sawing, except for Site W where sawing was conducted on the following day (Figure 8). Data shown in Figure 8 indicate that sawing should be conducted about 220 minutes after initial set. Sites A and L are two early entry saw cutting sites in MN whose sawing times fit well in the established relationship. Limestone was used in most early entry saw cutting sites except one site that contained quartzite. The hardness of aggregate may only affect the saw blade selection but not the sawing time (Eilken 2015).

The data for conventional sawing time shown in Figure 9 seem to indicate that once initial set is achieved, sawing should be started based upon the relationship in Equation 1, i.e., if initial set is between 150 and 500 minutes, saw cutting should be conducted about 310 to 390 minutes later. The mixtures used to establish the relationship consisted of limestone, granite and quartzite as coarse aggregate, which does not appear to have an effect on sawing times for the mixtures tested in this study. The red mark in Figure 9 is a result from a span saw which is much heavier than a typical conventional saw machine (Figure 10).

$$\text{Saw time} = 1.24 \times \text{initial set time(UPV)} + 273 \quad \text{Eq. 1}$$

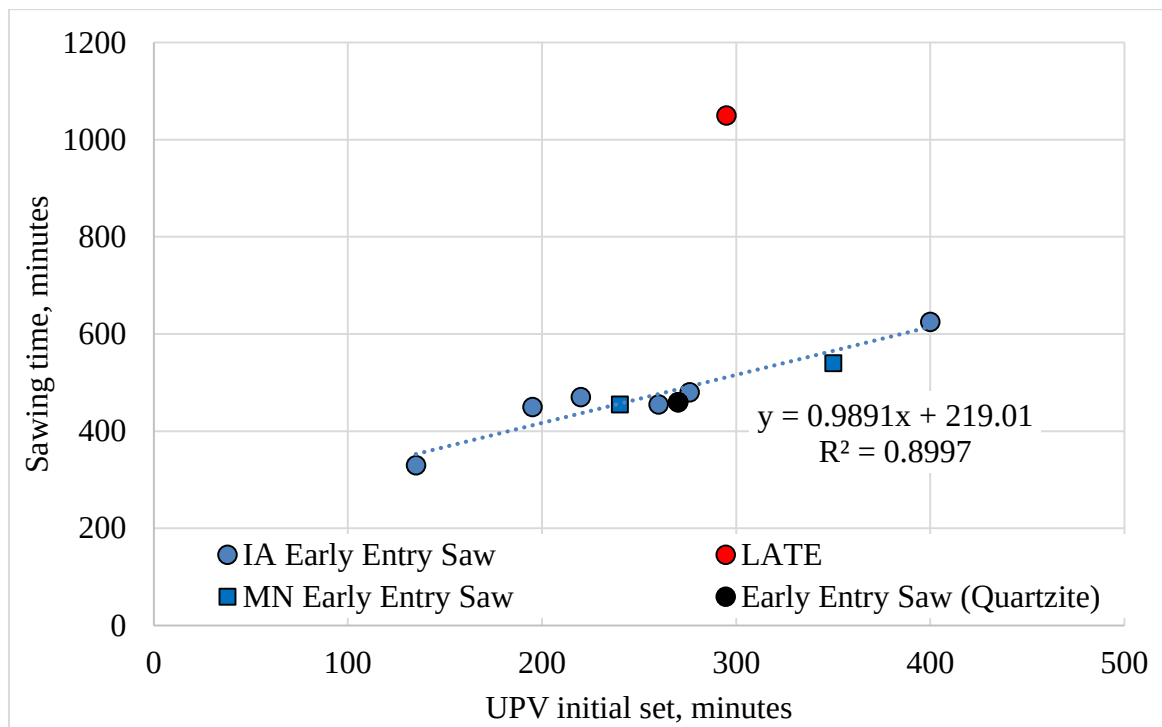


Figure 8. Early entry sawing time and initial set from UPV measurements (Taylor and Wang 2014)

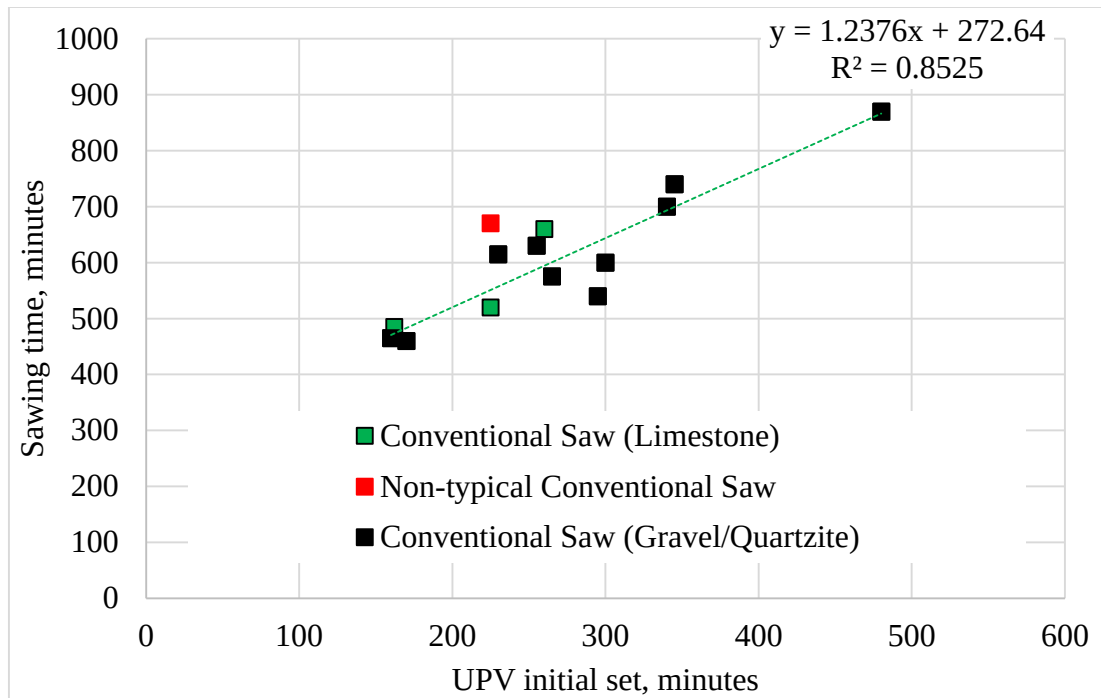


Figure 9. Conventional sawing time and initial set from UPV measurements (Taylor and Wang 2015)



Figure 10. A span saw machine used at Site B

From the calorimetry data shown in Figure 11, it can be observed that start temperatures on heat of hydration curves fall within a wide range from 13 to 27°C. The temperature rises are varied as well as the times to reach peak temperature, resulting in different initial set times for each site using 20% temperature rise of calorimetric fraction method.

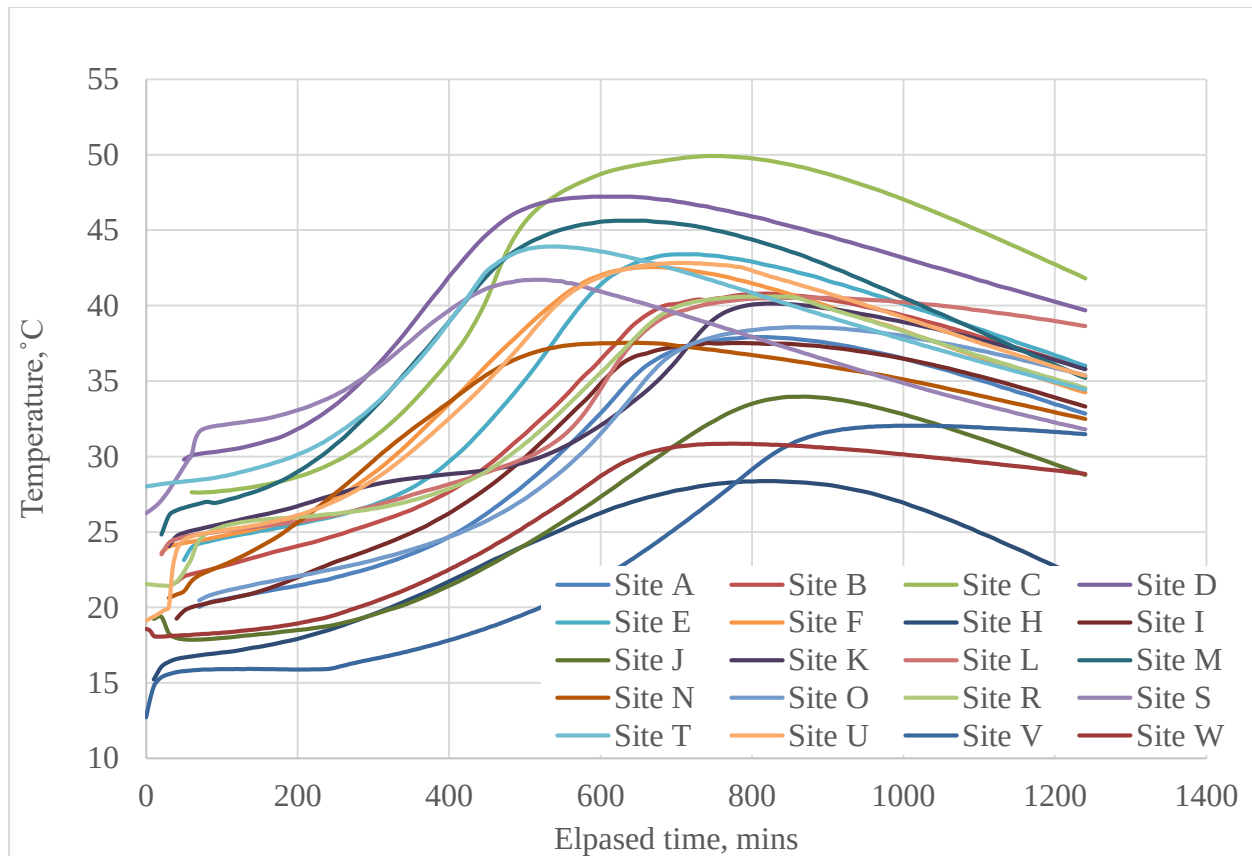


Figure 11. Calorimetry data for selected sites

It is recommended that when applying this UPV approach on site, contractors take UPV measurements for a given mixture several times during the first days in order to calibrate system. Thereafter, saw cutting can be predicted based on the calibration and the aforementioned relationship.

CONCLUSIONS

The data collected in this case study indicates the following:

- Proposed UPV approach looks promising for predicting saw cutting times in the field
 - Early entry saw: start sawing about 220 minutes after initial set
 - Conventional saw: start sawing about 310 to 390 minutes after initial set
- Compared to calorimetry fraction method, UPV measured initial set times seem to have a better correlation with initial set times measured in accordance with penetration resistance method.
- Aggregate types in the mixtures do not appear to affect the sawing time predicted by from the setting time.

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