# MECHANICAL PROPERTIES AND EARLY-AGE VOLUME CHANGE OF RAPID SETTING HYDRAULIC CEMENTS (RSHC)

by

Deep J. Kotadiya, B.E.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Technology Management
December 2021

Committee Members:

Anthony Torres, Chair

Federico Aguayo

Xijun Shi

## ACKNOWLEDGEMENTS

I would like to thank Lord Shiva and Ganesh, my parents, Jaysukh Kotadiya and Sharda Kotadiya, for their continuous love and support.

I would like to express my sincere gratitude to my committee members Dr. Federico Aguayo, Dr. Anthony Torres, and Dr. Xijun Shi, for their immense knowledge, enthusiasm, motivation, and patience that helped me throughout the research process. Also, undergraduate students for helping with physical work.

Lastly, I thank the faculty and staff in the Department of Engineering Technology for their continuous support throughout my research.

## TABLE OF CONTENTS

**Page**

ACKNOWLEDGEMENTS ........ iv

LIST OF TABLES ........ vii

LIST OF FIGURES ........ ix

LIST OF ABBREVIATIONS ........ xi

ABSTRACT ........ xii

CHAPTER

1. INTRODUCTION ........ 1

   1.1 Background ........ 1
   1.2 Statement of Problem ........ 2
   1.3 Research Significance ........ 4
   1.4 Research Objective ........ 4
   1.5 Assumptions ........ 4
   1.6 Limitations and Delimitations ........ 5

2. LITERATURE RIVIEW ........ 6

   2.1 Rapid Setting Hydraulic Cement (RSHC) ........ 6
      2.1.1 Calcium Sulfoaluminate Cement (CSA) ........ 7
         2.1.1.1 History and background ........ 7
         2.1.1.2 Cement chemistry, hydration, and application ........ 7
      2.1.2 Calcium Aluminate Cement (CAC) ........ 8
         2.1.2.1 History and background ........ 8
         2.1.2.2 Cement chemistry, hydration, and application ........ 8
      2.1.3 Blended system incorporating CSA or CAC with OPC ........ 9
         2.1.3.1 History and background ........ 9
         2.1.3.2 Hydration and application ........ 10
      2.1.4 Mechanical properties ........ 10

3. MATERIALS AND EXPERIMENTAL METHOD ........ 12

3.1 Materials ....................................................................................12
3.1.1 Straight cements..........................................................................15
3.1.2 Proprietary cements ....................................................................15
3.1.3 Laboratory blended Cements .......................................................15
3.2 Mix Proportion...............................................................................16
3.3 Experimental Method.....................................................................18
3.3.1 Fresh Properties ..........................................................................18
3.3.1.1 Apparatus ..................................................................................18
3.3.1.2 Procedure ..................................................................................18
3.3.1.2.1 Slump cone test .......................................................................18
3.3.1.2.2 Unit weight test .......................................................................19
3.3.1.2.3 Air content test ........................................................................19
3.3.1.2.4 Setting time of concrete ..........................................................19
3.3.2 Hardened Properties....................................................................20
3.3.2.1 Apparatus ..................................................................................20
3.3.2.2 Procedure ..................................................................................21
3.3.2.2.1 Compressive strength test .......................................................21
3.3.2.2.2 Splitting tensile strength test ...................................................21
3.3.2.2.3 Elastic modulus test ................................................................21
3.3.2.2.4 Drying shrinkage test ..............................................................22

4. RESULTS AND DISCUSSION ..........................................................23

4.1 Fresh Properties ..............................................................................23
4.1.1 Slump, unit weight and air content ...............................................23
4.1.2 Setting time of concrete ................................................................24
4.2 Hardened Properties.........................................................................32
4.2.1 Compressive strength....................................................................32
4.2.2 Splitting tensile strength ...............................................................39
4.2.3 Elastic modulus.............................................................................42
4.2.4 Drying shrinkage...........................................................................46

5. CONCLUSION AND RECOMMENDATIONS ....................................51

5.1 Conclusion .......................................................................................51
5.2 Future work.......................................................................................52

REFERENCES CITED.............................................................................53

## LIST OF TABLES

**Table** **Page**


1. Cement ID for different cement types ............................................................13
2. Chemical composition of different cements. .....................................................14
3. Mix matrix for 446 kg/$m^3$ cement binder. ..........................................................16
4. Mix matrix for 390 kg/$m^3$ cement binder. ..........................................................17
5. Fresh properties result for 446 kg/$m^3$ cement binder. .........................................23
6. Fresh properties result for 390 kg/$m^3$ cement binder. .........................................24
7. Setting time of straight cement mortar at 446 kg/$m^3$ cement binder. ..........................25
8. Setting time of proprietary cement mortar at 446 kg/$m^3$ cement binder......................26
9. Setting time of lab-blended cement mortar at 446 kg/$m^3$ cement binder. ...................27
10. Setting time of straight cement mortar at 390 kg/$m^3$ cement binder. ..........................28
11. Setting time of proprietary cement mortar at 390 kg/$m^3$ cement binder......................29
12. Setting time of lab-blended cement mortar at 390 kg/$m^3$ cement binder. ...................29
13. Compressive strength in Mpa at 446 kg/$m^3$ cement binder. .......................................32
14. Compressive strength in Mpa at 390 kg/$m^3$ cement binder. .......................................33
15. Splitting tensile strength in Mpa at 446 kg/$m^3$ cement binder. ...................................39
16. Splitting tensile strength in Mpa at 390 kg/$m^3$ cement binder. ...................................39
17. Modulus of elasticity results in Gpa at 446 kg/$m^3$ cement binder. .............................43
18. Modulus of elasticity results in Gpa at 446 kg/$m^3$ cement binder. .............................43
19. Drying shrinkage results for mixture at 446 kg/$m^3$ cement binder. ............................46

20. Drying shrinkage results for mixture at 390 $kg/m^3$ cement binder. ............................47

## LIST OF FIGURES


**Figure** **Page**

1. Chemical composition of different grades of CAC ....................................................9

2. Sieve Analysis for Limestone Rock.............................................................12

3. Sieve Analysis for River sand. ..........................................................................13

4. Setting time of straight cement mortar. .........................................................30

5. Setting time of proprietary cement mortar. ..................................................30

6. Setting time of lab blended cement mortar. ..................................................31

7. Compressive strength of CAC cement at 446 $kg/m^3$ cement binder. ............................33

8. Compressive strength of CSA cement at 446 $kg/m^3$ cement binder. ............................34

9. Compressive strength of PCSA cement at 446 $kg/m^3$ cement binder. ..........................34

10. Compressive strength of CAC cement at 390 $kg/m^3$ cement binder. ..........................35

11. Compressive strength of CSA cement at 390 $kg/m^3$ cement binder. ...........................35

12. Compressive strength of PCSA cement at 390 $kg/m^3$ cement binder..........................36

13. Splitting tensile strength of OPC 2, 3, CAC cement at 446 $kg/m^3$ cement binder. .....40

14. Splitting tensile strength of CSA cement at 446 $kg/m^3$ cement binder........................40

15. Splitting tensile strength of CAC cement at 390 $kg/m^3$ cement binder. ......................41

16. Splitting tensile strength of CSA cement at 390 $kg/m^3$ cement binder........................41

17. Modulus of elasticity for concrete mixtures at 446 $kg/m^3$ cement binder. ..................44

18. Modulus of elasticity for concrete mixtures at 390 $kg/m^3$ cement binder. ..................44

19. Drying shrinkage of prism demolded at 6h at 446 $kg/m^3$ cement binder. ...................48

20. Drying shrinkage of prism demolded at 1d at 446 kg/m$^3$ cement binder. ...................48

21. Drying shrinkage of prism demolded at 6h at 390 kg/m$^3$ cement binder. ...................49

22. Drying shrinkage of prism demolded at 1d at 390 kg/m$^3$ cement binder. ...................49

## LIST OF ABBREVIATIONS

| **Abbreviation** | **Description** |
|---|---|
| CSA | Calcium Sulfoaluminate Cement |
| CAC | Calcium Aluminate Cement |
| w/c | water-cement ratio |
| OPC | Ordinary Portland Cement |
| w/b | water-binder ratio |
| RSHC | Rapid setting hydraulic cement |
| RH | Relative Humidity |

## ABSTRACT

The mechanical properties of the calcium sulfoaluminate cement, calcium aluminate cement, and cement systems containing CSA or CAC with ordinary Portland cement at a w/c ratio of 0.35 are to be evaluated and compared to those of ordinary portland type I/II and type III cement. The samples at the total cement binder of 446 $kg/m^3$ and 390 $kg/m^3$, cures at standard room temperature $23^0C$ are to be tested.

The CSA and CAC influence the time of setting and compressive strength properties by showing the rapid strength increase at an early age. To obtain fresh properties, i) slump, ii) unit weight, iii) air content and iv) penetration (Time of setting) test, and hard properties, i) compressive strength, ii) tensile strength, iii) elastic modulus and iv) drying shrinkage test will be performed on several concrete mixes with different blends of cement contents.

# 1. INTRODUCTION

## 1.1 Background

Starting from the 1980s, major advances in understanding the hydration and material characterization of Portland cement took place(Schmidt et al., 2012). Soon after the increase in the use of supplementary cementitious materials (SCMs) and the raise of major chemical admixtures allowed the production of highly flowable concrete with a relatively low water-to-binder ratio(Schmidt et al., 2012). As a result of the combined effects of such special additives and admixtures, the use and implementation of concrete structures started to face a rapid growth due to the relative ease in procurement of OPC and the implementation of concrete structures.

About a few decades after this sustained growth, concrete structures face major structural deficiencies mainly due to durability issues (e.g., carbonation, freeze thawing) as well as overpassing their designed life expectancy. This can be seen from the recent report card published by the American Society of Civil Engineers (ASCE) that claimed a nearly 231,000 bridges in all 50 U.S. states are structurally deficient and require major repair and rehabilitation efforts to take place and requires about $125 billion immediate investment (ASCE's 2021).

As a result of the heavy cost of rebuilding major structures such as bridges and dams has forced significant efforts to take place in repair and rehabilitation practices of concrete structures. In that respect, a variety of cementing materials and binding agents including various polymer binders such as epoxy (Biolzi, Cattaneo, Guerrini, & Afroughsabet, 2020; Kumar, 2016) and polyester (Reis, 2012), alkali-activated materials (Mehrab Nodehi & Taghvaee, 2021), and rapid hardening binders such as Type III OPC

(Leung & Pheeraphan, 1995), CSA (Péra & Ambroise, 2004) and CAC (Torréns-Martín, Fernández-Carrasco, & Blanco-Varela, 2013) have been researched and often found to be promising. Among the mentioned, polymer binders, OPC type III, CSA and CAC are the most used materials and have found a variety of applications and uses especially for repair and rehabilitation practices.

Polymer binders, initially practiced as coating materials on bridge decks, mostly by Oregon and California Department of Transportation (ODOT and Caltrans, respectively) (M Nodehi, 2021), have been found to experience a major delamination and loss of strength due to the difference between the thermal coefficients of overlay polymer materials and the bridge decks (Fowler & Whitney, 2011). Although such issues have been later addressed and even to this date polymer resins are an integral part of repair and rehabilitation practices, their use is still relatively less cost effective if compared to alternative cementing materials such as OPC type III, CSA and CAC. Additionally, polymer binders are often considered unsustainable since after their use, the practice of recycling such thermosetting resins is considered unsustainable since after their use, the practice of recycling such thermosetting resins is considered to be impractical(M Nodehi, 2021). As a result, CSA, CAC and OPC type III are the most practiced repair binders.

**1.2 Statement of Problem**

The discovery and use of rapid hardening binder's dates to the 1900s with the early intention of developing sulfate resistant cement. The later commercialization of CACs in Europe and England during the 1910s and 1920s were the initial stages of developing rapid hardening cements (Bentivegna, 2012), (Mangabhai, 1990). Although CACs became very popular after their commercialization and used in numerous precast and refractory applications, they were found to experience a specific strength loss over time when exposed to sufficient moisture and moderate to high temperatures (Y. Zhang et al., 2018), (Gosselin, Gallucci, & Scrivener, 2010). This caused a few major structural failures and resulted in CACs being banned for use of the main structural applications during 1970s (Mangabhai, 1990). Later studies conducted on microstructural development and hydration of CACs reported that this type rapid hardening tend to go through a “conversion” process that specifically takes place when a w/c ratio of 0.4 or higher and a lower cement content of 400 kg/$m^3$ is used (K. L. Scrivener, Cabiron, & Letourneux, 1999). Such high w/c ratio and low cement content was a common practice, at the time, due to unavailability of superplasticizers (Mehrab Nodehi & Aguayo, 2021). This conversion process is reported be caused due to the nature of the hydrated materials that is accelerated in the presence of moisture (Bentivegna, 2012). The newly produced microstructural materials are found to have about only two third density of the initially produced materials (Hidalgo Lopez, García Calvo, García Olmo, Petit, & Alonso, 2008).

In the same way as CAC, CSA has been produced and practiced since the 1970s (Habert, 2014), for the purpose of making shrinkage resistant and self-stressing cements (Pimraksa & Chindaprasirt, 2018). CSA is made of bauxite, limestone, clay, and smaller quantity of other minerals such as gypsum or anhydrite at 1250-1350$^0$C in rotary kilns (Zhou, Milestone, & Hayes, 2006) to produce CSA or ye’elimite ($3CaO.3Al_2O_3.CaSO_4$). Due to the significantly high strength gain rate of CSA (almost twice of OPC (Ioannou, Paine, Reig, & Quillin, 2015)), dense micro structure and low hydration pH, and high impermeability, it has found a variety of applications. This includes precast and repair materials, as well as vast marine applications (Pimraksa & Chindaprasirt, 2018), (Xu, Ji, Yang, & Ye, 2019). According to Pimraksa et al. (2018), CSA produces only one third $CO_2$ when compared to OPC. Yet, due to the lower availability of bauxite, the transportation and processing of CSA's mineral ingredients, it is reported that CSA can be inefficient in terms of cost effectiveness when compared to the vast availability of limestone used in OPC production (Harrison, Jones, & Lawrence, 2019).

**1.3 Research Significance**

1. To generate fresh and hardened property data that will guide the use of RSHC and blends.
2. To generate short (early-age) and long-term compressive strength data, that will guide the application of these cements according to requirements.
3. To help reduce the emission of $CO_2$ from the production of cement by reducing the quantity of cement required for producing quality concrete.
4. To save time by gaining strength at early age.

**1.4 Research Objective**

The objective of this research is to evaluate the fresh and hardened properties of different CSAs, CACs and blends of CSA or CAC with OPC type I/II and compare the data with OPC type I/II and type III cements. The goal is to study the early rapid strength increase along with mass change in the RSHC.

**1.5 Assumptions**

1. The cements used to conduct the study is supplied from different manufacturer with the composition of those cements, which cannot be altered. Therefore, it is assumed that each cement used meets their respective standards or general expectations.

2. The concrete will be made on-site.
3. The samples will be cured and kept at desired temperature throughout the testing.

**1.6 Limitations and Delimitations**

1. Materials used for the study will meet ASTM standards but are sourced and produced locally and may not be available in all the regions.
2. Due to high cost of this rapid setting cements not much information is available and took time to get noticed in the construction industry.
3. The experiment will be conducted in a sheltered laboratory and with limited human resources.
4. Environmental factors like temperature, humidity, and other external factors limit the validity of other settings.
5. The study will not include details of the use of this concrete mix created because of the broad range of concrete applications.
6. The study may take longer because of the types of cement used and according to the manufacturer's availability.
7. The samples cast may not be cast with ease and results in voids due to the early setting behavior of the cement used.

# 2. LITERATURE REVIEW

## 2.1 Rapid Setting Hydraulic Cement (RSHC)

The OPC binder is the traditionally used cement binder in the construction industry. Replacing OPC with hydraulic cement could provide equivalent performance with lower $CO_2$ emission for an equal volume of concrete (Gartner, 2004). The alternative to OPC that achieves rapid setting, lesser $CO_2$ emission, early strength development, and less shrinkage can be CSA, CAC, or blend containing CSA, CAC with OPC type I/II.

Rapid setting cement has been used in high demand to repair pavements and bridge decks made of OPC. The material provided sufficient strength and durability, curing rapidly in high-traffic urban areas (Macadam, Smith, Fowler, & Meyer, 1984). To provide ample time for transportation, yet rapid setting concrete, chemical admixtures were added to the mixture before or during mixing to modify the fresh and hardened properties of concrete (Kosmatka, Kerkhoff, & Panarese, 2002; Macadam et al., 1984).

Earlier, research has been done on the physical properties of concrete with Ultimax (CSA cement and CSA additive manufacturing brand) RSHC compared with concrete containing OPC type I/II cement (Akthem A. Al-Manaseer & Hasan). Concrete made of Ultimax cement demonstrated a good workable slump of 7-1/8 in. and 41.9 MPa 1-day compressive strength at a low w/c of 0.30 was obtained without any admixtures, at 90 days, up to 74% less shrinkage and 69% less expansion compared to concrete made with OPC type I/II cement (Akthem A. Al-Manaseer & Hasan). The different components present in CSA and CAC compared to OPC make them uncommon but an innovative and convenient approach towards rapid construction of concrete bridges, pavement of highways, and roads.

The chemical admixtures are classified depending on the function, such as accelerating setting and early-strength development, improve workability, bonding, retard setting time, reducing w/c ratio, permeability, shrinkage, and many more. (Kosmatka et al., 2002). However, the effect of an admixture varies with the factors like addition rate, time of addition, composition; brand, type, and amount of cement; aggregate gradation and shape;  slump; mixing time; and temperature of the concrete (Kosmatka et al., 2002).

### 2.1.1 Calcium Sulfoaluminate Cement (CSA)

#### 2.1.1.1 History and background

The history, chemistry, performance, and use of belitic calcium Sulfoaluminate cement (BCSA) was investigated; BCSA has been developed in the US for more than 30 years. It is presented as a recent innovation. However, the use of this cement has exceeded two million tonnes in North America (Bescher & Kim, 2019). CSA cement got into interest for its low carbon footprint (Gartner, 2004). The CSA cement distinguishes itself from OPC by its high-speed bonding, fast strength development, and low shrinkage reduction (Al Horr, Elhoweris, & Elsarrag, 2017).

#### 2.1.1.2 Cement chemistry, hydration, and application

Belite ($C_2S$), yeelimitie or tetracalcium trialuminate sulfate ($C_4A_3S$), and gypsum ($CSH_2$) are primary constituents of CSA cement. When CSA cement hydrates in the presence of lime, the ettringite formed is expansive and is used in applications like shrinkage resistant and self-stressing cement, whereas ettringite produced in the absence of lime is non-expansive and results in high early strength (Péra & Ambroise, 2004).

CSA cement has been used since the 1970s as a binder in concrete for bridges, airport runways, road repair, and many others where quick reuse is necessary.

### 2.1.2 Calcium Aluminate Cement (CAC)

#### 2.1.2.1 History and background

CAC was introduced over 100 years ago; due to its conversion process while hydration and expensive cost, it was not used widely as OPC. Production of CAC has lower $CO_2$ emissions compared to the production of OPC. The CAC is known for its rapid strength gain, especially at lower temperatures, superior durability, and high-temperature resistance.

#### 2.1.2.2 Cement chemistry, hydration, and application

Calcium oxide (CaO) and aluminum oxide ($Al_2O_3$) are the main constituents of CAC, where $Al_2O_3$ content varies from 40-80% depending on the grade of CAC (Refer Table 1 for the composition ranges in different grade of CAC) (K. L. Scrivener et al., 1999). The hydration of CAC takes place in three phases, i) at $T < 15^0$C, hydrate forms is $CAH_{10}$, ii) at intermediate temperature, hydrate forms are $C_2AH_8$ and $AH_3$, and iii) at $T > 70^0$C, hydrate forms are $C_3AH_6$ and $AH_3$, where $CAH_{10}$ and $C_2AH_8$ correspond to the rapid increase in high early-age strength (K. L. Scrivener et al., 1999). According to Scrivener et al., a w/c ratio of 0.4 or less and cement content of 400 kg/m$^3$ or more is essential for long-term durability.

Today, CACs are used in refractory and building chemistry applications involving high temperatures, like floor screeds and rapid-hardening mortars (K. Scrivener & Capmas, 2003).

| Grade | Colour | $Al_2O_3$ | CaO | $SiO_2$ | $Fe_2O_3$ + FeO | $TiO_2$ | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|
| Standard low alumina | Grey or buff to black | 36–42 | 36–42 | 3–8 | 12–20 | <2 | ~1 | ~0.1 | ~0.15 |
| Low alumina, low iron | Light buff or grey to white | 48–60 | 36–42 | 3–8 | 1–3 | <2 | ~0.1 | ~0.1 | ~0.05 |
| Medium alumina | White | 65–75 | 25–35 | <0.5 | <0.5 | <0.05 | ~0.1 | <0.3 | ~0.05 |
| High alumina | White | ⩾80 | <20 | <0.2 | <0.2 | <0.05 | <0.1 | <0.2 | ~0.05 |

Fig 1. Chemical composition of different grades of CAC.(K. L. Scrivener et al., 1999)

### 2.1.3 Blended system incorporating CSA or CAC with OPC.

#### 2.1.3.1 History and background

OPC is being used as a hydraulic binder traditionally for building structures. Nevertheless, the production of OPC emits around 5% of total worldwide man-made $CO_2$ emissions (Juenger, Winnefeld, Provis, & Ideker, 2011). Although CSA cement has low carbon footprint, the blend of CSA-OPC cement can be utilized to combine the benefits and control particular properties (Trauchessec, Mechling, Lecomte, Roux, & Le Rolland, 2015). Similarly, blends of CAC-OPC were considered for rapid setting and appreciable strength like sealing of leaks and road repair(Gu, Beaudoin, Quinn, & Myers, 1997).

### 2.1.3.2 Hydration and application

The stability of ettringite as the main hydration product of CSA, ye'elimite ($C_4A_3S$), is related to the pH value of the matrix; the addition of OPC can increase the pH value of the CSA matrix (Zhang, Li, Yang, Ren, & Song, 2018). According to Zhang et al., the presence of OPC in CSA cement can guarantee the CSA late strength development and stability of ettringite. The rapid formation of ettringite in the hydration of the CAC-OPC blend can provide rapid setting and quick strength development(Gu et al., 1997).

### 2.1.4 Mechanical Properties

One of the major benefits of CSA and CAC are their mechanical properties that compared to OPC is reported to be around two times higher(Qin, Gao, & Zhang, 2018). Many studies have been done on the mechanical properties of CSA, CAC, and blends containing CSA or CAC with OPC. For example, the setting time and compressive strength of ternary blend consist of CSA, CAC and OPC was studied and concluded that (i) the content of CAC-OPC is directly related to the setting time and strength, (ii) the increase in strength with the time of ternary blends resulted from low porosity (J. Zhang et al., 2018). Also, The addition of CSA cement can accelerate the setting and hardening process and improve the early age strength, which is favorable for construction (Qin et al., 2018). The OPC-CSA blend cement display higher early strength, exhibited enhanced resistance to the early frost damage and has a higher hydration rate and larger amount of heat of hydration compared to OPC (Li, Gao, Wang, Tam, & Li, 2020). The CSA cement percentage modifies the hardening speed in CSA-OPC blend (Trauchessec et al., 2015).

Very few data is available for the fresh properties of the rapid setting hydraulic cement. An adequate and stable air-void system is necessary to guarantee resistance to freezing and thawing (Khayat & Assaad, 2002). A reduction of 60% of $CO_2$ emissions and energy consumption can be obtained by replacing OPC with supplementary cementitious materials (SCMs)/ lime (CH) (Coppola, Coffetti, Crotti, & Pastore, 2018). The setting time of PC-CSA blend decreases with higher dosage of CSA cement, accelerating period is postponed, compressive strength increased at early age but decreased at late age and good resistance to early age frost at -$5^0$C can be obtained by adding 20% CSA cement (Qin et al., 2018).

The study reveals that 3h compressive strength of cement mixture increases remarkably with the addition of a mechanically activated $Al(OH)_3$-$Ca(OH)_2$ mixture(Kitamura, Kamitani, & Senna, 2000). The mechanical strength is lower in high alkalinity, due to formation of different reaction products (Tambara Jr, Cheriaf, Rocha, Palomo, & Fernández-Jiménez, 2020). The addition of ethylene-vinyl acetate (EVA) and methylcellulose into ternary system can improve stability of ettringite and increase the compressive and flexural strength (Shi, Zou, & Wang, 2020). The citric acid reduces CAC-OPC cement strength at all concentration levels and lactic acid below 2% weight improves both the compressive and flexural strength at early ages (Kastiukas, Zhou, Castro-Gomes, Huang, & Saafi, 2015). Keeping in mind the effects of admixture on several properties of cement, the admixtures such as 10% Sika NC and 1.75% GCX as an accelerator, citric acid not more than 1% as a retarder, and Viscocrete 4100 less than 1% as a high range water reducer (HRWR) to control the workability and setting time of concrete.

## 3. MATERIALS AND EXPERIMENTAL METHOD

### 3.1 Materials

The fine and coarse aggregates utilized were fine river sand and crushed limestone rock sourced from a local quarry in Texas. Fig. 2 and 3 show the sieve analysis of crushed limestone rock and river sand. Table 1. shows the cement ID and Table 2. represents the chemical composition provided for the different cement types. The types of cement are categorized as straight cement, proprietary cement, and lab blended cement. All the materials were kept at room temperature for at least 24 hours before mixing.

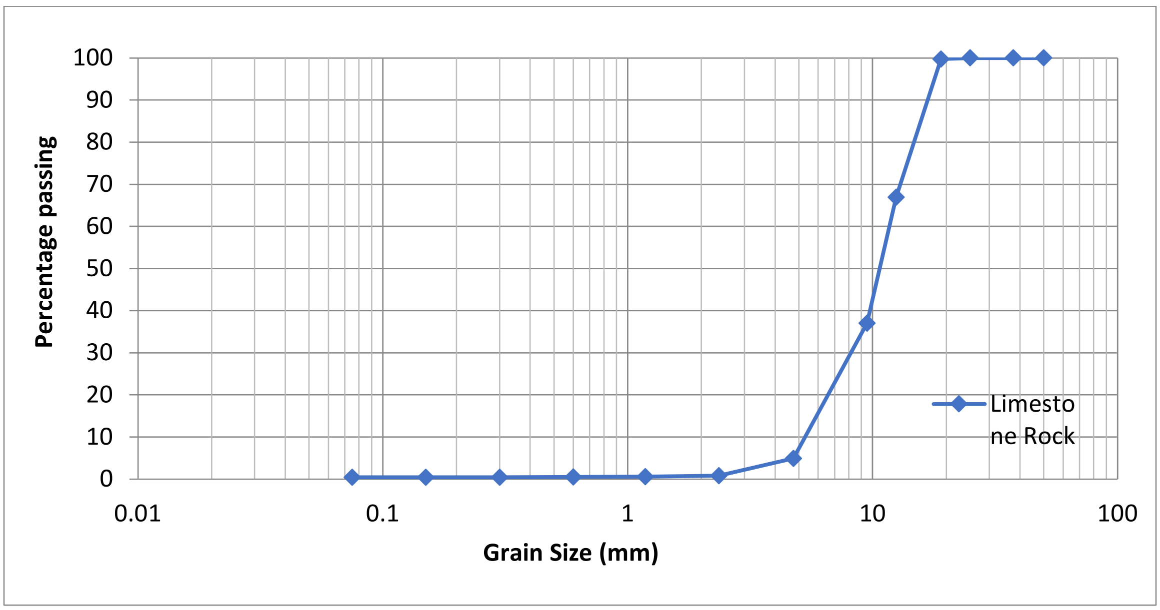


Fig. 2 Sieve Analysis for Limestone Rock.

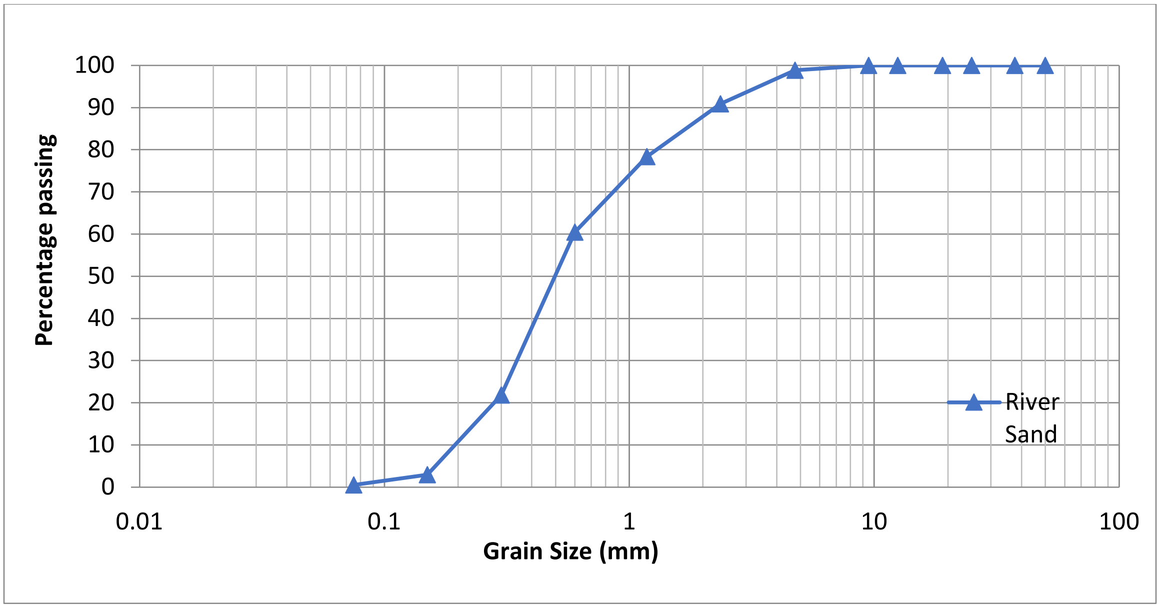


Fig. 3 Sieve Analysis for River sand.

Table 1. Cement ID for different cement types.

| Cement Type | Cement ID | Cement Category | Information |
|---|---|---|---|
| **Straight Cement** | OPC 2 | Portland | Ordinary Portland Cement Type I and II |
| | OPC 3 | Portland | Ordinary Portland Cement Type III |
| | CAC 1 | Calcium Aluminate | Calcium Aluminate Cement |
| | CSA 1 | Calcium Sulfoaluminate | Calcium Sulfoaluminate cement with low belite system |
| | CSA 2 | Calcium Sulfoaluminate | Calcium Sulfoaluminate cement with high belite system |
| **Proprietary Cement** | CAC1 B1 | Calcium Aluminate | Cement based on Calcium Aluminate cement and OPC |
| | CAC1 B2 | Calcium Aluminate | Preblend of Calcium Aluminate cement with Class C Fly Ash |
| | CSA2 B1 | Calcium Sulfoaluminate | Preblend of CSA with pozzolan and mineral admixtures |
| | CSA2 B2 | Calcium Sulfoaluminate | Preblend of CSA with pozzolan and mineral admixtures |
| | PCSA 1 | Calcium Sulfoaluminate | Preblend Calcium Sulfoaluminate cement |
| | PCSA 2 | Calcium Sulfoaluminate | Preblend Calcium Sulfoaluminate cement with different chemistry and/or fineness |
| **Lab Blended Cement** | CAC1 OPC2 | Calcium Aluminate | Pure CAC blended with OPC Type I/II |
| | CSA1 OPC2 | Calcium Sulfoaluminate | Pure CSA blended with OPC Type I/II |

Table 2. Chemical composition of different cements.

| **Cement Type** | **Cement ID** | **SiO2** | **Al2O3** | **Fe2O3** | **CaO** | **MgO** | **SO3** | **Na2O** | **K2O** | **Na2Oe** | **P2O5** | **Cl** | **TiO2** | **MnO** | **ZnO** | **Cr2O3** | **LOI** | **CO2** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Straight Cement** | OPC 2 | 21.06 | 4.02 | 3.19 | 63.91 | 1.08 | 2.89 | 0.14 | 0.61 | 0.53 | 0.11 | 0.011 | 0.18 | 0.027 | 0.050 | 0.007 | 2.29 | 1.52 |
| | OPC 3 | 19.67 | 5.34 | 1.76 | 63.41 | 0.99 | 5.27 | 0.10 | 0.44 | 0.39 | 0.29 | 0.012 | 0.23 | 0.025 | 0.007 | 0.010 | 4.06 | 1.19 |
| | CAC 1 | 4.34 | 38.65 | 15.09 | 38.37 | 0.39 | 0.16 | 0.05 | 0.14 | 0.14 | 0.12 | 0.003 | 1.82 | 0.114 | 0.020 | 0.108 | 1.55 | 0.64 |
| | CSA 1 | 9.07 | 21.61 | 2.26 | 45.26 | 0.94 | 20.26 | 0.07 | 0.30 | 0.27 | 0.07 | 0.008 | 0.76 | 0.073 | 0.013 | 0.015 | 1.05 | 0.27 |
| | CSA 2 | 20.56 | 16.14 | 1.35 | 45.31 | 1.23 | 14.73 | 0.77 | 0.72 | 1.24 | 0.16 | 0.015 | 0.76 | 0.011 | 0.019 | 0.016 | 4.74 | 1.81 |
| **Proprietary Cement** | CAC1 B1 | 13.46 | 12.23 | 2.67 | 56.65 | 2.86 | 9.90 | 0.20 | 0.79 | 0.72 | 0.11 | 0.007 | 0.60 | 0.143 | 0.073 | 0.037 | 1.21 | 0.54 |
| | CAC1 B2 | 12.71 | 32.94 | 12.95 | 35.09 | 1.79 | 0.84 | 0.50 | 0.24 | 0.65 | 0.30 | 0.010 | 1.70 | 0.093 | 0.017 | 0.089 | 1.23 | 0.36 |
| | CSA2 B1 | 13.63 | 15.82 | 0.75 | 51.28 | 1.14 | 16.62 | 0.29 | 0.62 | 0.69 | 0.15 | 0.018 | 0.72 | 0.012 | 0.017 | 0.016 | 3.06 | 1.28 |
| | CSA2 B2 | 14.72 | 14.37 | 1.22 | 53.85 | 1.23 | 14.40 | 0.10 | 0.59 | 0.49 | 0.15 | 0.017 | 0.65 | 0.036 | 0.010 | 0.017 | 3.39 | 1.76 |
| | PCSA 1 | 17.38 | 11.06 | 2.98 | 55.82 | 1.25 | 10.68 | 0.43 | 0.52 | 0.77 | 0.12 | 0.010 | 0.58 | 0.072 | 0.015 | 0.012 | 2.26 | 1.25 |
| | PCSA 2 | 20.14 | 15.73 | 3.52 | 43.90 | 1.55 | 12.88 | 0.59 | 0.52 | 0.93 | 0.23 | 0.010 | 0.75 | 0.064 | 0.021 | 0.026 | 1.95 | 0.82 |
| | | | | | | | | | | | | | | | | | | |
| **Lab Blended Cement** | CAC1 OPC2 | 15.80 | 3.02 | 2.39 | 47.93 | 0.81 | 2.16 | 0.10 | 0.45 | 0.40 | 0.08 | 0.01 | 0.14 | 0.02 | 0.04 | 0.01 | 1.72 | 1.14 |
| | CSA1 OPC2 | 18.06 | 8.42 | 2.96 | 59.25 | 1.04 | 7.23 | 0.12 | 0.53 | 0.47 | 0.10 | 0.01 | 0.33 | 0.04 | 0.04 | 0.01 | 1.98 | 1.21 |

### 3.1.1 Straight cements

Straight cement means pure cement. Cement ID OPC 2 and OPC 3 are given to OPC Type I and II, and rapid setting OPC Type III, cement ID CAC 1 is given to Calcium Aluminate cement and has the highest content of aluminum (Table 2), and cement ID CSA 1 and CSA 2 are given to cement-based on Calcium Sulfoaluminate cement with low and high belite system.

### 3.1.2 Proprietary cements

Proprietary cement is preblended cement supplied by the manufacturer. Cement ID CAC1 B1 and CAC1 B2 are based on Calcium Aluminate cement mixed with OPC and Class C fly ash, CSA2 B1, CSA2 B2, PCSA 1 and PCSA 2 are all Calcium Sulfoaluminate based cement with different chemical composition and/or fineness.

### 3.1.3 Laboratory blended cements

Lab blended cement is planned in the lab by mixing OPC Type I/II with CSA or CAC cement. Cement ID CAC1 OPC2 is made by mixing 25% CAC with 75% OPC I/II. Similarly, cement ID CSA1 OPC2 is produced by mixing 25% CSA with 75% OPC I/II.

### 3.2 Mix Proportion

The fresh and hardened properties for all the cement types are listed in Table. 1 with a cement binder of 446 kg/m$^3$, and all cement types hardened properties with a 390 kg/m$^3$ at a 0.35 w/c ratio are to be evaluated. Tables 3 and 4 show the detailed mix matrix planned for the research.

Table 3. Mix matrix for 446 kg/m$^3$ cement binder.

| Cement Type | Cement ID | w/c ratio | Total binder (kg/m3) | Control Binder (%) | Type I/II (%) |
|---|---|---|---|---|---|
| **Straight Cement** | OPC 2 | 0.35 | 446.00 | 100 | 0 |
| | OPC 3 | 0.35 | 446.00 | 100 | 0 |
| | CAC 1 | 0.35 | 446.00 | 100 | 0 |
| | CSA 1 | 0.35 | 446.00 | 100 | 0 |
| | CSA 2 | 0.35 | 446.00 | 100 | 0 |
| **Proprietary Cement** | CAC1 B1 | 0.35 | 446.00 | 100 | 0 |
| | CAC1 B2 | 0.32 | 446.00 | 100 | 0 |
| | CSA2 B1 | 0.35 | 446.00 | 100 | 0 |
| | CSA2 B2 | 0.35 | 446.00 | 100 | 0 |
| | PCSA 1 | 0.35 | 446.00 | 100 | 0 |
| | PCSA 2 | 0.35 | 446.00 | 100 | 0 |
| **Lab Blended Cement** | CAC1 OPC2 | 0.35 | 446.00 | 25 | 75 |
| | CSA1 OPC2 | 0.35 | 446.00 | 25 | 75 |

Table 4. Mix matrix for 390 kg/m$^3$ cement binder.

| Cement Type | Cement ID | w/c ratio | Total binder (kg/m3) | Control Binder (%) | Type I/II (%) |
|---|---|---|---|---|---|
| Straight Cement | CAC 1 | 0.35 | 390.00 | 100 | 0 |
| | CSA 1 | 0.35 | 390.00 | 100 | 0 |
| | CSA 2 | 0.35 | 390.00 | 100 | 0 |
| Proprietary Cement | CAC1 B1 | 0.35 | 390.00 | 100 | 0 |
| | CSA2 B1 | 0.35 | 390.00 | 100 | 0 |
| | CSA2 B2 | 0.35 | 390.00 | 100 | 0 |
| | PCSA 1 | 0.35 | 390.00 | 100 | 0 |
| | PCSA 2 | 0.35 | 390.00 | 100 | 0 |
| Lab Blended Cement | CAC1 OPC2 | 0.35 | 390.00 | 25 | 75 |
| | CSA1 OPC2 | 0.35 | 390.00 | 25 | 75 |

## 3.3 Experimental Method

### 3.3.1 Fresh Properties

The fresh properties of concrete mixes that are slump, unit weight, air content, and setting time (Penetration) of concrete are carried out. The fresh properties of all the mix design in Table 3 at a w/c ratio of 0.35 and cement binder of 446 kg/$m^3$ is determined. Further, all the tests will be performed according to ASTM standard methods.

#### 3.3.1.1 Apparatus

The apparatus used for the fresh properties of concrete are slump metal cone mold, tamping rod, ruler, scoop, and a base plate as mentioned in section 5 of ASTM C143/C143M–15a to measure the slump of concrete. A digital weighing machine, tamping rod with a diameter of 5/8 $\pm$ 1/16 inch (16 $\pm$ 2 mm) and a cylindrical measuring bowl container as per section 4.4 of ASTM C138/C138M – 17a to measure the density of the concrete. An air meter, the same measuring bowl used for unit weight, tamping rod, syringe, and funnel as described in section 4 of ASTM C173/C173M–16 to know air content in concrete. A cylindrical container for mortar specimen that is watertight, rigid, and free of oil and grease, penetration needles with bearing areas of 1, ½, ¼, 1/10, 1/20, and 1/40 in.$^2$, and loading apparatus to measure penetration force as in section 6 of ASTM C403/C403M-16 to determine the setting time of concrete.

#### 3.3.1.2 Procedure

##### 3.3.1.2.1 Slump cone test

The sample from each concrete mix in Table 3 is used to perform the slump cone test, according to ASTM C143/C143M-15a. The slump between 3 and 9 inches is considered good workability, again depending on its application.

#### 3.3.1.2.2 Unit weight test

The fresh sample of concrete is collected from each mix prepared in Table 3 and filled in a container of volume 0.25 $m^3$. The empty weight of the container is 7.38 lbs. The weight of the container filled with concrete is noted. A container filled with concrete minus the container's empty weight will provide the weight of concrete divided by the volume of the container, i.e., 0.25 $m^3$ will be calculated to determine the unit weight of concrete, according to ASTM C138/C138M-17a.

#### 3.3.1.2.3 Air content test

The same container filled with concrete used in the unit weight test is used for the air content test. The air meter is attached on the top of the measuring bowl. The air content reading is noted from the meter in percentage, according to ASTM C173/C173M.

#### 3.3.1.2.4 Setting time of concrete

A mortar sample is obtained by sieving the fresh sample and is filled in a cylindrical container; the container is stored at a specified ambient temperature of 23 $^0$C. The concrete is filled to a depth of at least 5½ inches. The resistance of the specimen to penetration by standard needles will be measured at a regular time interval. The precise distance between the needle impressions and the side of the container was at least 1 inch. (25 mm), but not more than 2 inches (50 mm). The test is performed according to ASTM C403/C403M-16 time of setting of the mortar sample by penetration resistance. The force in pounds is noted at a regular time interval with the size of the needle used. The readings are taken until it exceeds 4000 psi to plot a graph between pressure resisted with elapsed time. The penetration test will be performed mainly every 5 min. interval starting at a random time after water and cement contact because CSA has high early time of setting. In contrast, CAC starts to set a little later. Different types of cement have different time of setting depending on their chemical composition.

### 3.3.2 Hardened Properties

The hardened properties of concrete mixes are evaluated: compressive strength, tensile strength, elastic modulus, and drying shrinkage. The hardened properties of all the mix design in Table 3 and 4 at a w/c ratio of 0.35 and cement binder of 446 kg/m$^3$ and 390 kg/m$^3$ is determined. Overall, 28 cylinders and six prisms were cast from each concrete mix.

#### 3.3.2.1 Apparatus

The apparatus used to perform hardened properties test are as follow: compression testing machine, upper and lower steel bearing blocks, and solid steel spacers as per section 6 in ASTM C39/C39M-18 to determine the compressive strength of concrete samples. The splitting tensile test on cylindrical concrete specimens was performed on the same testing machine as above, with supplementary plates and two thick plywood bearing strips mentioned in ASTM C496/C496M-17. The same testing machine and compressometer were used to determine the elastic modulus of concrete samples as mentioned in ASTM C469/C469M-14. A length comparator, steel molds for casting test specimens, and a weighing scale were used to determine drying shrinkage in beam samples as mentioned in ASTM C157/C157M-17.

#### 3.3.2.2 Procedure

##### 3.3.2.2.1 Compressive strength test

The compressive strength test was performed under ASTM C39/C39M-18. Unbonded bearing steel plates were attached on top and bottom of the concrete specimen to ensure even distribution of load on sample surface during the test. Twenty-four cylindrical concrete samples of dimension 4 x 8 inches (100 x 200 mm) were cast for each mixture prepared in Tables 3 and 4. The average compressive strength of three cylindrical concrete samples will be noted at 3h, 6h, 8h, 1d, 3d, 7d, 28d, and 91d, making it a total of 24. The samples were kept in the curing room after demolding at 24h until the testing age.

##### 3.3.2.2.2 Splitting tensile strength test

The splitting strength test was carried out as per ASTM C496/C496M-17. The supplementary plates were used to provide the desired height for the testing of the specimen. The cylindrical concrete sample is rested on thick plywood bearing strip. Another strip is kept on top to ensure even distribution of load. Four cylindrical concrete samples of the same dimension used in the compressive strength test were cast for each mixture prepared in Tables 3 and 4. The average reading of two samples was noted at 1d and 28d ages, respectively.

##### 3.3.2.2.3 Elastic modulus test

The elastic modulus test was done following ASTM C469/C469M-14. The elastic modulus and compressive strength were determined alongside at ages 7d and 28d, respectively. Three cylindrical concrete specimens were used to perform the test, out of which two samples were sulfur capped in accordance with ASTM C617 as prescribed in

ASTM C469/C469M-14. Firstly, one sample without sulfur capping was tested for strength with unbounded steel caps, and the ultimate load was noted. Secondly, a compressometer was attached to the cylinder specimen with sulfur capping and used to read the specimen's longitudinal strain (deformation) when the sample was subjected to compressive loading. Thirdly, the applied load and longitudinal strain were noted at 50 microstrains and 40% of the ultimate load of the first cylindrical concrete specimen. Lastly, the specimen was then loaded to failure, and 40% of its ultimate load was noted to determination the elastic modulus of the last sulfur-capped cylindrical concrete specimen, which went through the same process before it was loaded to failure.

#### 3.3.2.2.4 Drying shrinkage test

The drying shrinkage test was performed in accordance with ASTM C157/C157M-17. Six prisms of dimension 3 x 3 x 11.25 inches (75 x 75 x 281.25 mm) were cast with concrete from each mix prepared in Tables 3 and 4. The three prisms were demolded at 6h and other three were demolded at 24h. After, demolding the samples were kept in an environmental chamber, the temperature was maintained at 23 $\pm$ 2 $^0$C (73 $\pm$ 3 $^0$F) and an RH of 50 $\pm$ 4 %. An initial reading of three prisms demolded at 6h, and the other three prisms demolded at 24h are noted from the compressometer. Subsequent readings were taken in an environmental chamber on a compressometer for all six concrete prisms at 4d, 7d, 28d, 56d, 112d, and 224d.

# 4. RESULTS AND DISCUSSIONS

## 4.1 Fresh Properties

### 4.1.1 Slump, unit weight, and air content

The fresh properties (slump, unit weight, and air content) for all the mixtures in Tables 3 and 4 are given in Tables 5 and 6. Table 5 represents the fresh properties of the mixture in Table 3 at a cement binder of 446 kg/m$^3$. Table 6 shows the fresh properties of mixture in Table 4 at a cement binder of 390 kg/m$^3$.

Table 5. Fresh properties result for 446 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Total binder (kg/m$^3$) | Slump (inches) | Unit weight (kg/m$^3$) | Air content (%) |
|---|---|---|---|---|---|
| Straight Cement | OPC 2 | 446 | 5 | 2394.03 | 1.1 |
| | OPC 3 | 446 | 3.5 | 2369.2 | 2 |
| | CAC 1 | 446 | 1.5 | 2356.86 | 0.5 |
| | CSA 1 | 446 | 9 | 2315.85 | 1.8 |
| | CSA 2 | 446 | 10.25 | 2350.45 | 3.2 |
| Proprietary Cement | CAC1 B1 | 446 | 7 | 2364.55 | 2.4 |
| | CAC1 B2 | 446 | 4.25 | 2355.58 | 4 |
| | CSA2 B1 | 446 | 10.5 | 2374.8 | 4 |
| | CSA2 B2 | 446 | 3.5 | 2424.79 | 1.1 |
| | PCSA 1 | 446 | 9 | 2319.7 | 1.3 |
| | PCSA 2 | 446 | 10 | 2345.33 | 1.4 |
| Lab Blended Cement | CAC1 OPC2 | 446 | 2.5 | 2386.34 | 2.3 |
| | CSA1 OPC2 | 446 | 5 | 2394.03 | 2.3 |

Table 6. Fresh properties result for 390 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Total binder (kg/m3) | Slump (inches) | Unit weight (kg/m3) | Air content (%) |
|---|---|---|---|---|---|
| Straight Cement | CAC 1 | 390 | 3 | 2406.84 | 1.6 |
| | CSA 1 | 390 | 0.5 | 2396.59 | 0.8 |
| | CSA 2 | 390 | 9.25 | 2372.24 | 2.8 |
| Proprietary Cement | CAC1 B1 | 390 | 0.5 | 2409.4 | 2.1 |
| | CSA2 B1 | 390 | 8.5 | 2359.43 | 2.7 |
| | CSA2 B2 | 390 | 1.75 | 2395.31 | 2.5 |
| | PCSA 1 | 390 | 8 | 2408.13 | 1.9 |
| | PCSA 2 | 390 | 8 | 2401.72 | 2.4 |
| Lab Blended Cement | CAC1 OPC2 | 390 | 3.5 | 2387.62 | 2.5 |
| | CSA1 OPC2 | 390 | 1.5 | 2360.71 | 2.4 |

### 4.1.2 Setting time of concrete

Tables 7 shows the test result for the setting time of mortar for the straight cement mixture in Table 3 at cement binder of 446 kg/m$^3$. Similarly, Tables 8 and 9 displays the time of setting data for the proprietary and lab-blended cement mortar for 446 kg/m$^3$ cement binder. Tables 10, 11 and 12 shows the penetration result of the cement mortar for the straight, proprietary, and lab-blended cement concrete mixture in Table 4 at a cement binder of 390 kg/m$^3$.

The penetration resistance values in psi and elapsed time in minutes are used to plot a graph of penetration resistance versus elapsed time, according to ASTM C403/C403M-16. Fig. 4, 5 and 6 represent the graph plotted for straight, proprietary, and lab blended cement mortar at a cement binder of 446 and 390 kg/m$^3$, and w/c ratio of 0.35, respectively. The graph provides a better understanding of the comparison of setting time of cement mortar at 446 and 390 kg/m$^3$ cement binder.

Table 7. Setting time of straight cement mortar at 446 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Elapsed Time (min.) | Penetration Resistance, (psi) |
|---|---|---|---|
| Straight Cement | OPC 2 | 122 | 40 |
| | | 143 | 80 |
| | | 165 | 212 |
| | | 180 | 360 |
| | | 197 | 600 |
| | | 216 | 1840 |
| | | 235 | 3040 |
| | | 263 | 4960 |
| | | 285 | 6240 |
| | OPC 3 | 90 | 720 |
| | | 150 | 1440 |
| | | 160 | 1960 |
| | | 170 | 2520 |
| | | 180 | 4000 |
| | CAC 1 | 60 | 208 |
| | | 70 | 216 |
| | | 80 | 376 |
| | | 90 | 488 |
| | | 110 | 592 |
| | | 205 | 800 |
| | | 265 | 840 |
| | | 595 | 1120 |
| | CSA 1 | 60 | 8000 |
| | CSA 2 | 55 | 40 |
| | | 75 | 488 |
| | | 80 | 800 |
| | | 100 | 8000 |

Table 8. Setting time of proprietary cement mortar at 446 kg/m$^3$ cement binder.

| **Cement Type** | **Cement ID** | **Elapsed Time (min.)** | **Penetration Resistance, (psi)** |
|---|---|---|---|
| Proprietary Cement | CAC1 B1 | 74 | 40 |
| | | 90 | 44 |
| | | 100 | 128 |
| | | 126 | 400 |
| | | 127 | 448 |
| | | 135 | 544 |
| | | 150 | 1100 |
| | | 165 | 2200 |
| | | 170 | 3520 |
| | | 175 | 4720 |
| | CAC1 B2 | 64 | 44 |
| | | 90 | 384 |
| | | 112 | 2000 |
| | | 117 | 2200 |
| | | 118 | 4240 |
| | CSA2 B1 | 46 | 40 |
| | | 66 | 488 |
| | | 71 | 800 |
| | | 91 | 8000 |
| | CSA2 B2 | 30 | 40 |
| | | 40 | 176 |
| | | 45 | 368 |
| | | 50 | 840 |
| | | 55 | 1680 |
| | | 60 | 6400 |
| | PCSA 1 | 127 | 328 |
| | | 140 | 8000 |
| | PCSA 2 | 100 | 272 |
| | | 108 | 5680 |
| | | 111 | 6400 |
| | | 130 | 8000 |

Table 9. Setting time of lab-blended cement mortar at 446 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Elapsed Time (min.) | Penetration Resistance, (psi) |
|---|---|---|---|
| Lab Blended Cement | CAC1 OPC2 | 40 | 124 |
| | | 42 | 240 |
| | | 45 | 336 |
| | | 47 | 440 |
| | | 50 | 700 |
| | | 52 | 860 |
| | | 57 | 1380 |
| | | 60 | 2240 |
| | | 65 | 3200 |
| | | 73 | 8000 |
| | CSA1 OPC2 | 135 | 140 |
| | | 152 | 260 |
| | | 177 | 392 |
| | | 195 | 700 |
| | | 215 | 2560 |
| | | 220 | 3680 |
| | | 235 | 8000 |

Table 10. Setting time of straight cement mortar at 390 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Elapsed Time (min.) | Penetration Resistance, (psi) |
|---|---|---|---|
| Straight Cement | CAC 1 | 100 | 156 |
| | | 115 | 184 |
| | | 135 | 216 |
| | | 145 | 240 |
| | | 160 | 272 |
| | | 173 | 464 |
| | | 180 | 528 |
| | | 190 | 536 |
| | | 205 | 600 |
| | | 255 | 675 |
| | | 375 | 8000 |
| | CSA 1 | 49 | 152 |
| | | 63 | 600 |
| | | 80 | 8000 |
| | CSA 2 | 128 | 200 |
| | | 136 | 472 |
| | | 144 | 780 |
| | | 153 | 1680 |
| | | 155 | 6160 |
| | | 175 | 8000 |

Table 11. Setting time of proprietary cement mortar at 390 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Elapsed Time (min.) | Penetration Resistance, (psi) |
|---|---|---|---|
| Proprietary Cement | CAC1 B1 | 67 | 224 |
| | | 76 | 368 |
| | | 83 | 920 |
| | | 93 | 1300 |
| | | 105 | 1880 |
| | | 106 | 2320 |
| | | 119 | 6880 |
| | | 123 | 8000 |
| | CSA2 B1 | 76 | 48 |
| | | 80 | 80 |
| | | 90 | 148 |
| | | 110 | 8000 |
| | CSA2 B2 | 62 | 52 |
| | | 70 | 132 |
| | | 80 | 344 |
| | | 85 | 520 |
| | | 90 | 1200 |
| | | 99 | 8000 |

Table 12. Setting time of lab-blended cement mortar at 390 kg/m$^3$ cement binder.

| Cement Type | Cement ID | Elapsed Time (min.) | Penetration Resistance, (psi) |
|---|---|---|---|
| Lab Blended Cement | CAC1 OPC2 | 107 | 132 |
| | | 122 | 232 |
| | | 145 | 760 |
| | | 163 | 1040 |
| | | 180 | 2440 |
| | | 185 | 3240 |
| | | 190 | 6080 |
| | | 195 | 6800 |
| | | 200 | 7200 |
| | CSA1 OPC2 | 135 | 140 |
| | | 152 | 260 |
| | | 177 | 392 |
| | | 195 | 700 |
| | | 215 | 2560 |
| | | 220 | 3680 |
| | | 235 | 8000 |

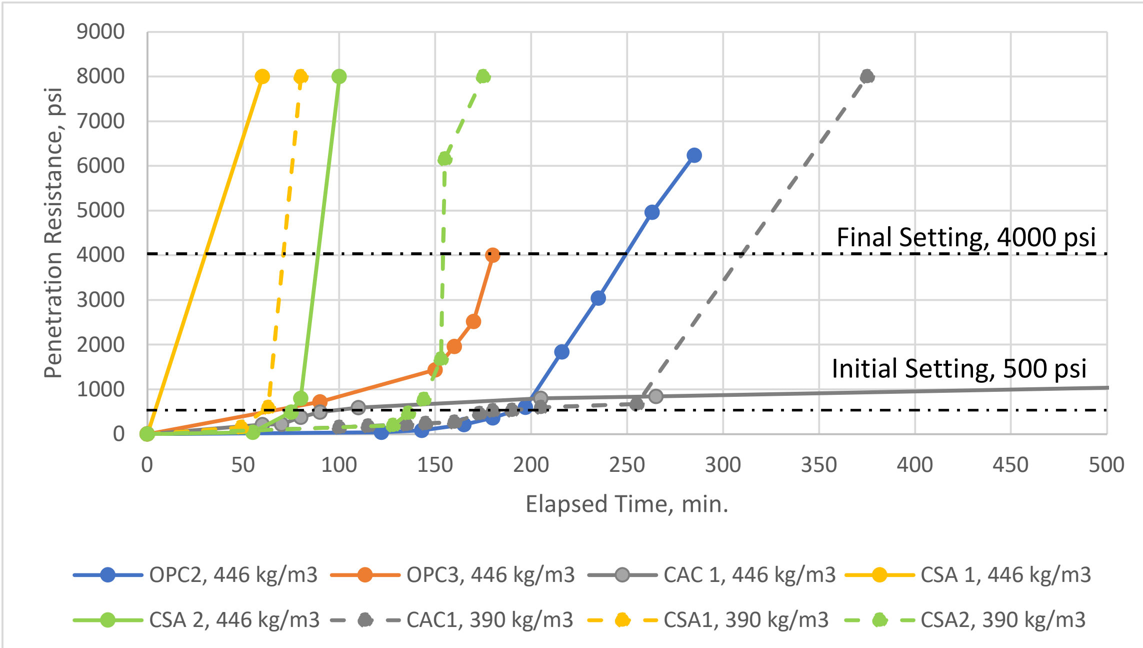


Fig. 4 Setting time of straight cement mortar.

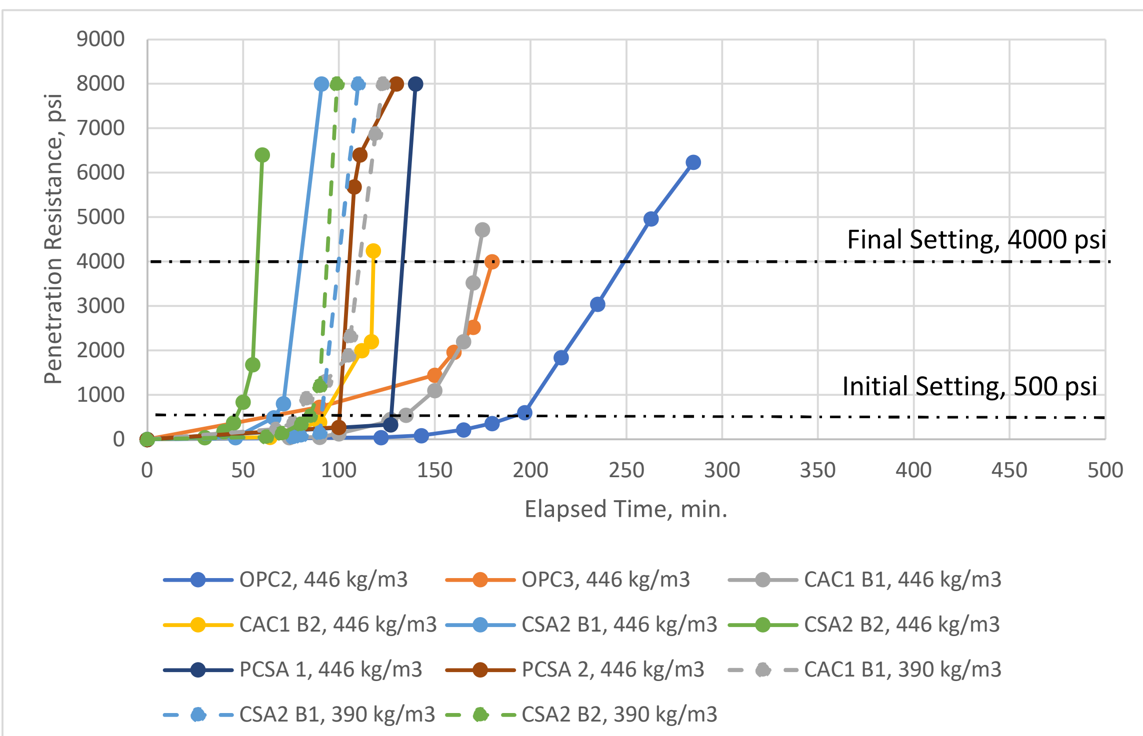


Fig. 5 Setting time of proprietary cement mortar.

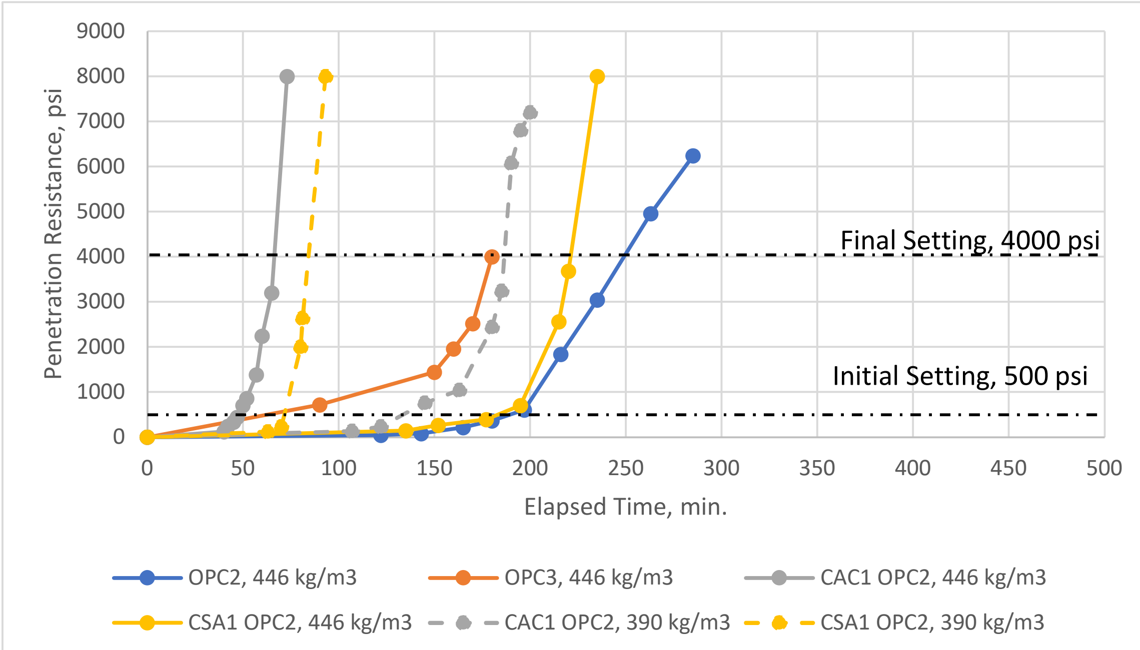


Fig. 6 Setting time of lab-blended cement mortar.

The setting time of OPC 2 and OPC 3 are included in all three figures, making it the base parameter for comparing setting times with different cement types. In all the figures 4, 5, and 6 straight lines are plotted for setting time of mortar mixture at cement binder of 446 kg/m$^3$. The dashed line represents the setting time of mortar at cement binder 390 kg/m$^3$.

From fig. 4 and 5, it can be determined that straight cement CAC setting time is more than OPC 2 and OPC 3. The higher the CAC cement amount gentler is the setting time. However, for CSA cement it is opposite higher the cement binder faster is the setting time. Nevertheless, for the lab-blended cement its vice-versa.

## 4.2 Hardened Properties

### 4.2.1 Compressive strength

For the compressive strength data, the average of strength of three cylindrical concrete samples were taken at all ages for concrete mixtures in Tables 3 and 4. Table 13 showcast compressive strength result in Mpa for concrete mixture at 446 kg/m$^3$ cement binder and w/c ratio of 0.35, with an exception of w/c ratio of 0.32 for CAC1 B2. And the compressive strength of concrete mixtures at 390 kg/m$^3$ cement binder and w/c ratio of 0.35 are displayed in Table 14.

Table 13. Compressive strength in Mpa at 446 kg/m$^3$ cement binder.

| **Cement ID** | **w/c ratio** | **Cement Binder (kg/m3)** | **Age** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **3h** | **6h** | **8h** | **1d** | **3d** | **7d** | **28d** | **91d** |
| OPC 2 | 0.35 | 446 | 0.69 | 1.44 | 3.53 | 26.18 | 48.31 | 57.41 | 61.69 | 79.39 |
| OPC 3 | 0.35 | 446 | 2.01 | 11.07 | 23.97 | 45.15 | 59.51 | 65.5 | 69.45 | 83.05 |
| CAC 1 | 0.35 | 446 | N/A | N/A | N/A | 6 | 32.12 | 35.04 | 47.16 | 56.69 |
| CSA 1 | 0.35 | 446 | 34.13 | 41.34 | 41.6 | 48.28 | 55.89 | 53.06 | 54.73 | 68.16 |
| CSA 2 | 0.35 | 446 | 37.07 | 47.79 | 50.14 | 45.67 | 55.43 | 56.21 | 52.33 | 62.8 |
| CAC1 B1 | 0.35 | 446 | 1.05 | 23.8 | 25.63 | 30.34 | 43.01 | 41.56 | 57.72 | 61.46 |
| CAC1 B2 | 0.32 | 446 | 0.99 | 13.48 | 20.6 | 32.97 | 38.74 | 39.63 | 45.33 | 56.38 |
| CSA2 B1 | 0.35 | 446 | 48.15 | 59.54 | 73.74 | 75.93 | 77.27 | 74.45 | 60.7 | 80.8 |
| CSA2 B2 | 0.35 | 446 | 35.47 | 38.41 | 44.62 | 47.46 | 49.51 | 50.92 | 64.25 | 65.26 |
| PCSA 1 | 0.35 | 446 | 6.01 | 29.24 | 30.19 | 33.23 | 40.26 | 40.85 | 28.76 | 50.26 |
| PCSA 2 | 0.35 | 446 | 7.85 | 10.15 | 25.49 | 33.95 | 35.42 | 32.74 | 38.17 | 44.63 |
| CAC1 OPC2 | 0.35 | 446 | 9.1 | 13.06 | 15.54 | 35.36 | 37.13 | 41.8 | 59.75 | 63.24 |
| CSA1 OPC2 | 0.35 | 446 | 1.95 | 10.15 | 11.78 | 15.19 | 27.11 | 35.09 | 53.3 | 65.96 |

Table 14. Compressive strength in Mpa at 390 kg/m$^3$ cement binder.

| Cement ID | w/c ratio | Cement Binder (kg/m3) | Age | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3h | 6h | 8h | 1d | 3d | 7d | 28d | 91d |
| CAC 1 | 0.35 | 390 | N/A | 0.58 | 5.45 | 38.32 | 40.05 | 40.77 | 41.99 | 53.51 |
| CSA 1 | 0.35 | 390 | 17.45 | 38.03 | 42.26 | 48.23 | 53.73 | 55.14 | 53.1 | 66.04 |
| CSA 2 | 0.35 | 390 | 0.14 | 24.06 | 28.83 | 34.57 | 37.96 | 36.02 | 38.51 | 42.91 |
| CAC1 B1 | 0.35 | 390 | 14.78 | 19.51 | 18.93 | 39.06 | 35.47 | 31.11 | 47.89 | 61.34 |
| CSA2 B1 | 0.35 | 390 | 29.6 | 46.87 | 48.35 | 52.81 | 54.52 | 42.85 | 51.45 | 64.58 |
| CSA2 B2 | 0.35 | 390 | 12.54 | 28.79 | 33.46 | 44.31 | 50.19 | 47.82 | 47.82 | 64.01 |
| PCSA 1 | 0.35 | 390 | 3.02 | 20.94 | 29.03 | 28.32 | 28.76 | 35.72 | 48.17 | 65.44 |
| PCSA 2 | 0.35 | 390 | 7.06 | 23.8 | 29.51 | 34.32 | 38.17 | 39.98 | 44.38 | 36.69 |
| CAC1 OPC2 | 0.35 | 390 | N/A | 6.08 | 6.48 | 9.21 | 24.1 | 23.09 | 54.1 | 60.07 |
| CSA1 OPC2 | 0.35 | 390 | 6.48 | 6.89 | 8.07 | 10.12 | 17.76 | 18.35 | 48.66 | 67.03 |

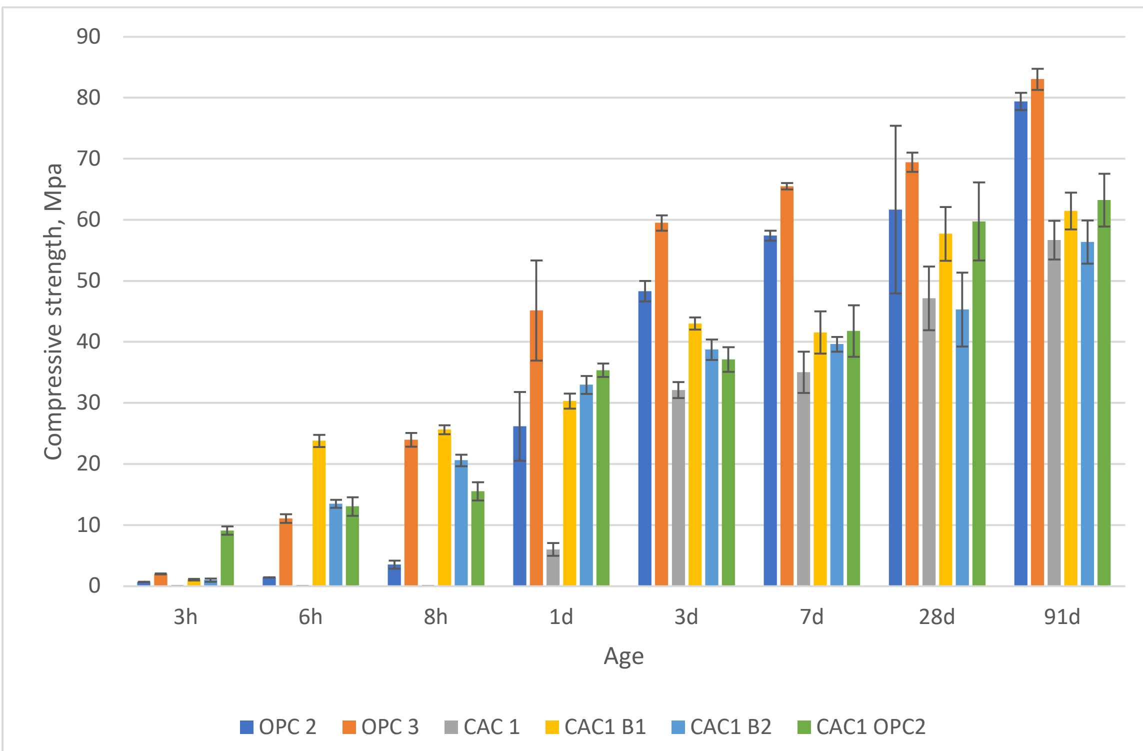


Fig. 7 Compressive strength of CAC cement at 446 kg/m$^3$ cement binder.

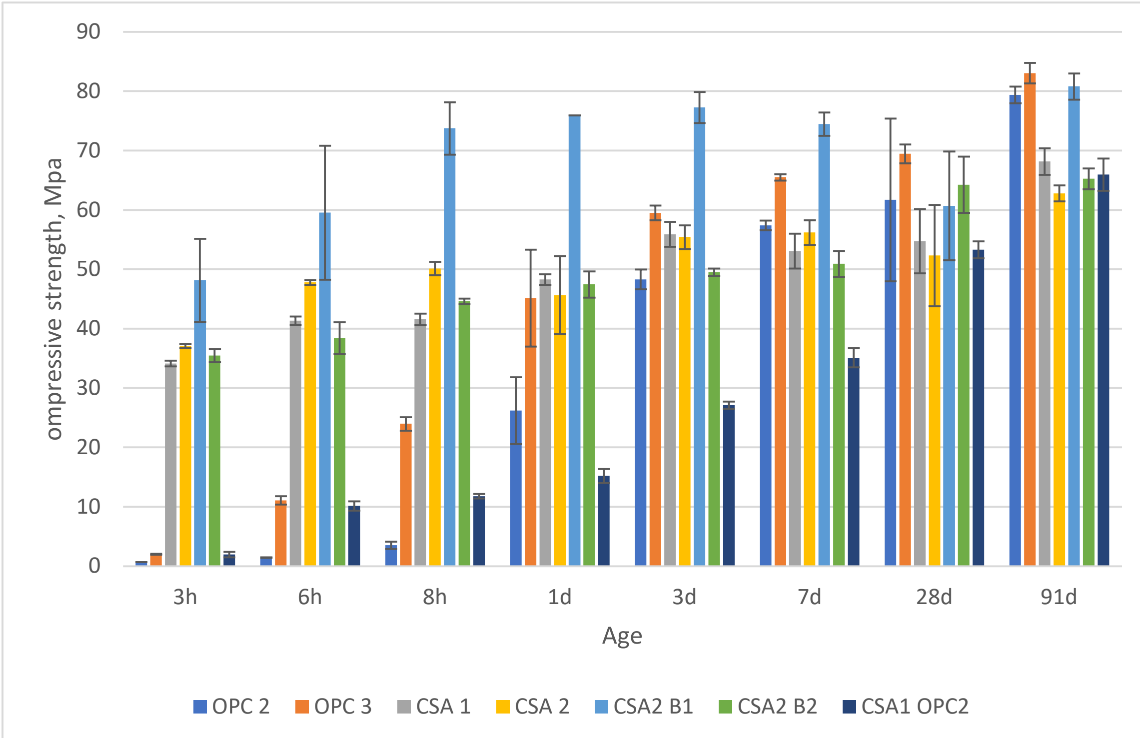


Fig. 8 Compressive strength of CSA cement at 446 kg/m$^3$ cement binder.

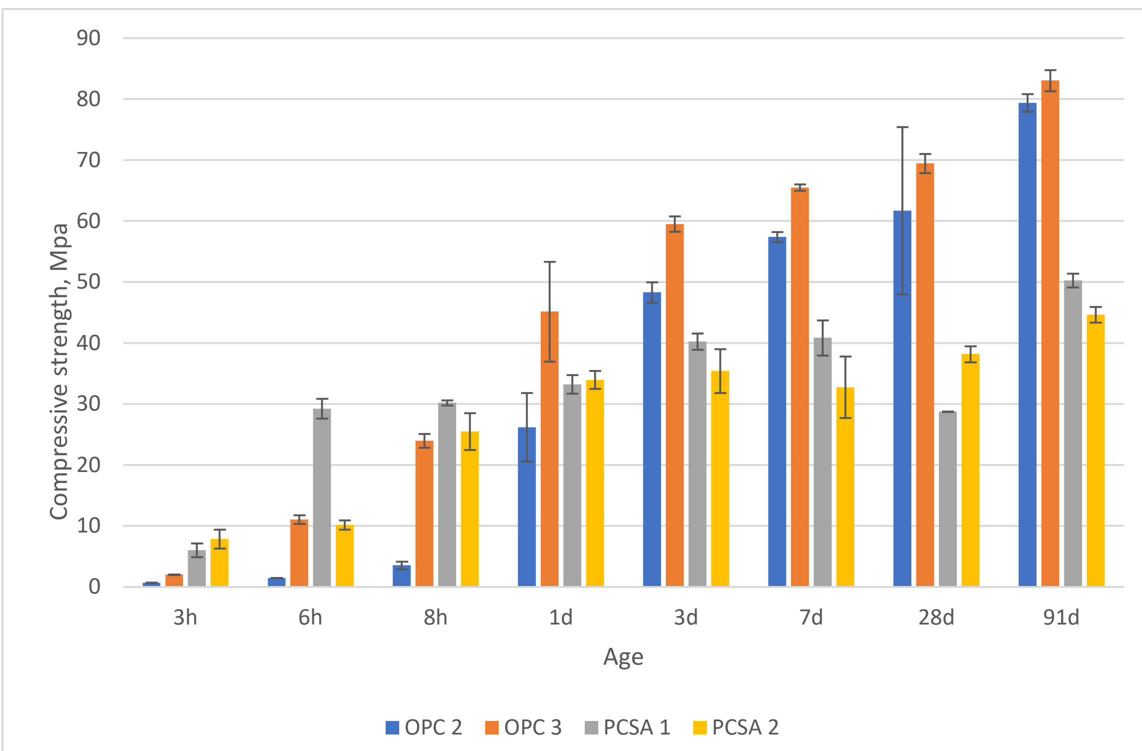


Fig. 9 Compressive strength of PCSA cement at 446 kg/m$^3$ cement binder.

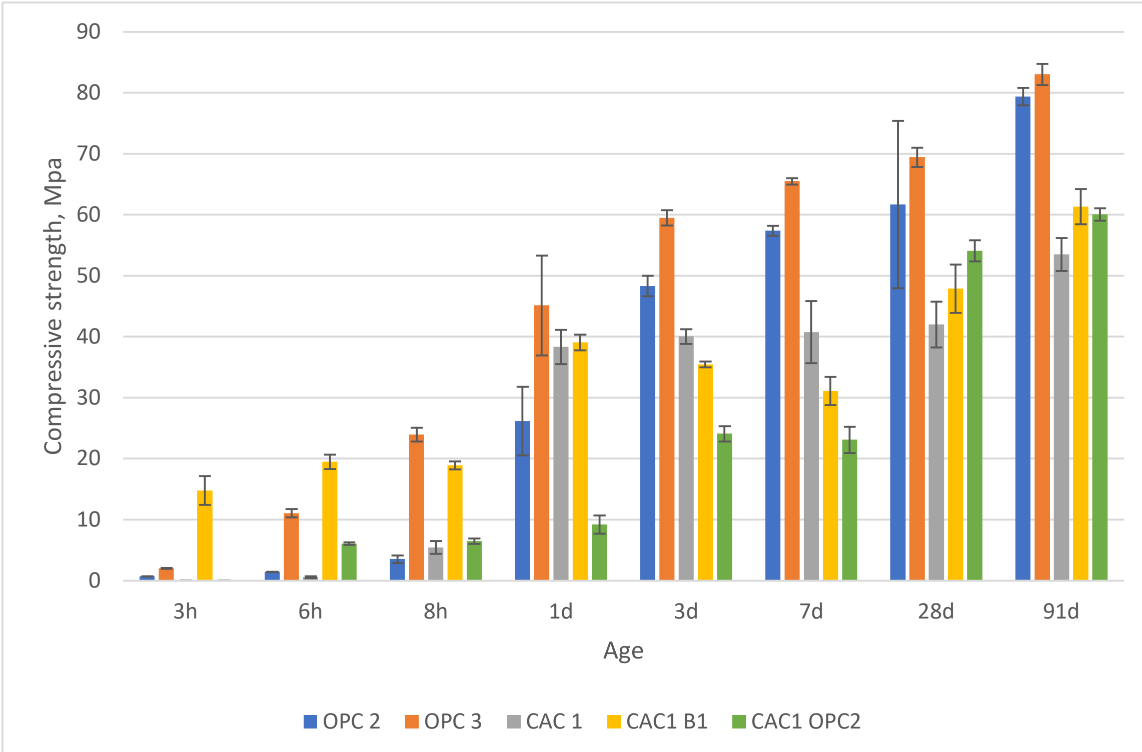


Fig. 10 Compressive strength of CAC cement at 390 kg/m$^3$ cement binder.

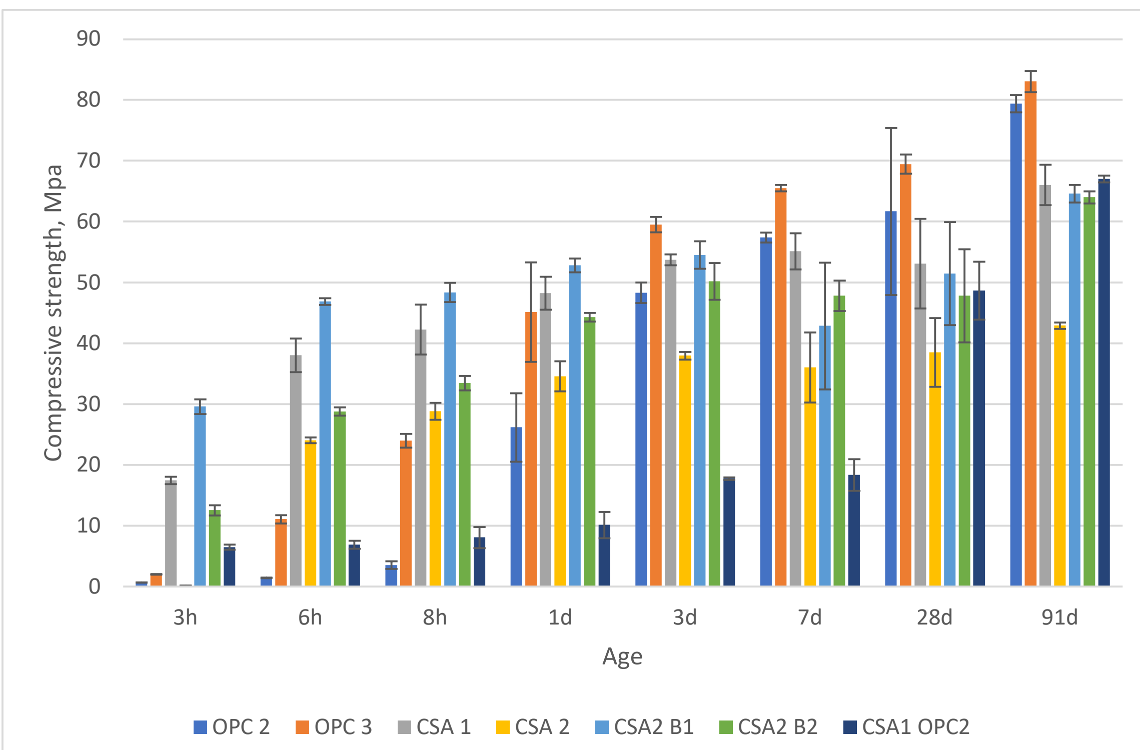


Fig. 11 Compressive strength of CSA cement at 390 kg/m$^3$ cement binder.

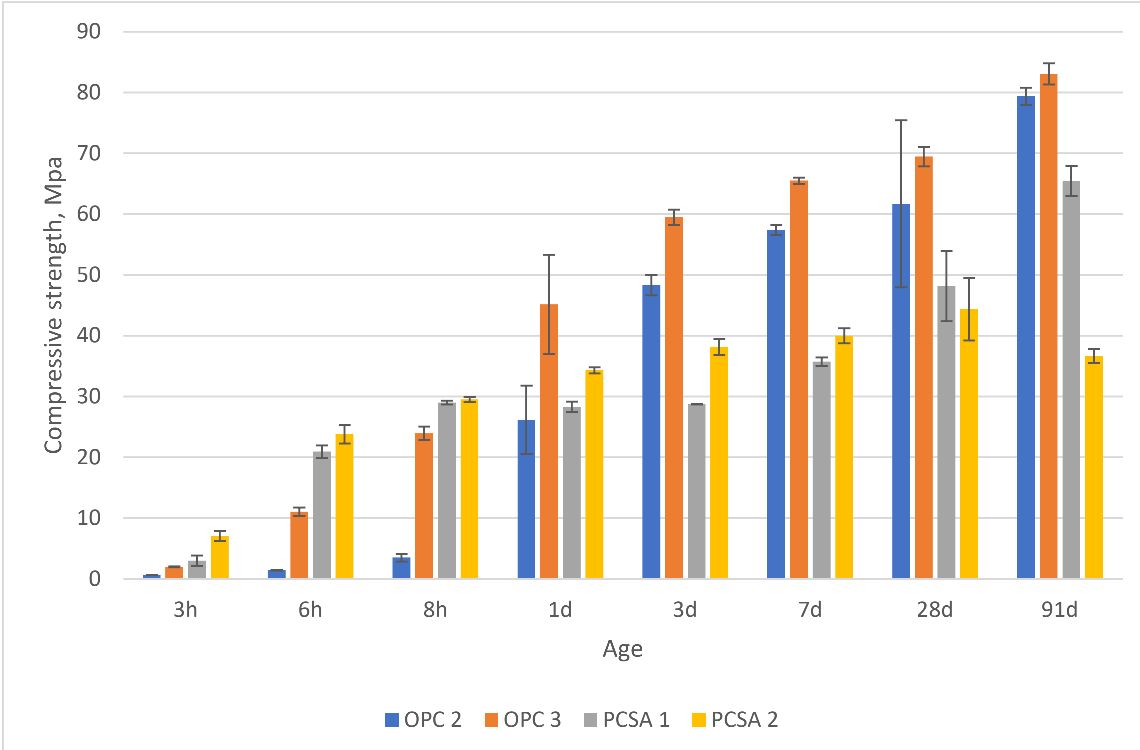


Fig. 12 Compressive strength of PCSA cement at 390 kg/m$^3$ cement binder.

Fig. 7, 8 and, 9 show the compressive strength data of CAC, CSA, and PCSA cement at 446 kg/m$^3$ cement binder and 0.35 w/c ratio, at 3h, 6h, 8h, 1d, 3d, 7d, 28d, and 91d, respectively. Whereas fig. 10, 11, and 12 represent the compressive strength data of CAC, CSA, and PCSA cement at 390 kg/m$^3$ cement binder and 0.35 w/c ratio. CAC1 B2 was only performed at 446 kg/m$^3$ cement binder and 0.32 w/c ratio, as suggested by the manufacturer, to get the best result. The OPC 2 and OPC 3 are set as base parameters to compare the strength of rapid setting cements.

Fig. 7 shows the compressive strength data for a straight, proprietary, lab blended CAC cement mixture at 446 kg/m$^3$ cement binder. The compressive strength of OPC 3 increases rapidly with age, gaining strength of more than 80 Mpa at 91d age. The strength of OPC 2 rises slowly at an early age but reaches around 80 Mpa at 91d age. The lab blended cement CAC1 OPC2 gains the strength of almost 10 Mpa within 3h, proprietary cement CAC1 B1 shows the highest strength at 6h compared to all other CAC and has significantly less iron content. At 91d age, all the CAC cement has strength of around 60 Mpa, 20 Mpa lesser than OPC 2 and OPC 3. CAC1 did not settle until 1d age, and it contains the most extensive aluminum and iron. Fig. 8 compares the compressive strength data of CSA cements at 446 kg/m$^3$ cement binder. The rapid gain in strength of CSA cements can be witnessed in fig. 8; CSA2 B1 shows extreme strength gain of around 50 Mpa within just 3h, and other CSA cement achieving gain of around 35 Mpa except lab blended CSA1 OPC2 less than 5 Mpa at 3h. CSA2 B1 has the lowest content iron compared to all other cement types. It acquires the highest strength of around 75 Mpa within 8h and maintains its strength at around 80 Mpa at 91d age, showing a slight reduction in strength at 7d and 28d. CSA 1, CSA 2, and CSA2 B2 shows rapid boost in strength at 3h of around 35 Mpa and increases gradually till around 65 Mpa at 91d age. However, CSA1 OPC2 takes 7d to reach strength of around 35 Mpa but has almost the same strength as others at 91d age. Fig. 9 compares the strength of PCSA cements with the strength of OPC 2 and OPC3 at 446 kg/m$^3$ cement binder. PCSA1 gains the strength of 30 Mpa at 6h increases gradually till 40 Mpa at 7d and reduces to 30 Mpa at 28d and again increases to 50 Mpa at 91d age. PCSA2 gains the compressive strength to 35 Mpa at 1d and reaches the strength of 45 Mpa at 91d age.

Fig. 10 compares the compressive strength data of CAC cements at 390 kg/m$^3$ cement binder. Again, CAC1 did not set until 6h. At 3h age, CAC1 B1 achieves a strength of 15 Mpa, CAC1 and CAC1 OPC2 did not even set. However, at 1d age, CAC1 and CAC1 B1 has almost the same strength of around 40 Mpa, the strength of CAC1 OPC is at around 10 Mpa. But, at 91d age, all CAC cement has a strength between 55-60

Mpa. Fig. 11 compares the compressive strength result of CSA cements at 390 $kg/m^3$ cement binder. CSA2 has the lowest strength of around 45 Mpa at 91d, whereas all other CSA cement gains the strength of around 65 Mpa. At 3d age, OPC 2 and OPC 3 acquire the compressive strength almost more than all other CSA cement strength. Fig. 12 helps understand the compressive strength of PCSA cements with age at 390 $kg/m^3$ cement binder. Both PCSA1 and PCSA2 start resisting load at 3h and 6h, having the almost same strength of 30 Mpa at 8h. However, at 91d age, PCSA1 gains the strength of almost 65 Mpa, but PCSA2 resists load around 45 Mpa at 28d age and reduces the strength to around 35 Mpa at 91d age.

All in all, for CAC cement lower cement binder of 390 $kg/m^3$ result in early age rapid strength gain compared to 446 $kg/m^3$ cement binder. CAC1 has the highest chemical composition of aluminum oxide and iron oxide. It contains the lowest amount of sulfite, which cause the delay in gaining the compressive strength at an early age but the content of calcium guarantee almost equal or closer compressive strength as other CAC cements. For CSA cement, it is opposite higher cement binder of 446 $kg/m^3$ result in early age rapid strength gain compared to 390 $kg/m^3$ cement binder. CSA cement is rich in sulphite content but contains almost half the aluminum oxide and significantly less iron oxide content compared to CAC cement, which results in early age rapid gain in compressive strength. The long-term gain in the compressive strength depends on the amount of calcium; OPC 2 and OPC 3 have a significant calcium content compared to all other CAC, and CSA hence has the highest compressive strength at 91d.

### 4.2.2 Splitting tensile strength

Tables 15 and 16 represent the splitting tensile strength of concrete mixtures prepared in Tables 3 and 4, at 1d and 28d age, at 446 and 390 kg/m$^3$ cement binder.

Table 15. Splitting tensile strength in Mpa at 446 kg/m$^3$ cement binder.

| Cement ID | w/c ratio | Cement Binder (kg/m3) | Age | |
|---|---|---|---|---|
| | | | **1d** | **28d** |
| OPC 2 | 0.35 | 446 | 6.41 | 9.58 |
| OPC 3 | 0.35 | 446 | 6.92 | 7.96 |
| CAC 1 | 0.35 | 446 | 1.46 | 4.72 |
| CSA 1 | 0.35 | 446 | 4.97 | 5.12 |
| CSA 2 | 0.35 | 446 | 9.17 | 8.15 |
| CAC1 B1 | 0.35 | 446 | 4.94 | 6.64 |
| CAC1 B2 | 0.32 | 446 | 4.57 | 3.69 |
| CSA2 B1 | 0.35 | 446 | 7.39 | 7.11 |
| CSA2 B2 | 0.35 | 446 | 4.67 | 5.11 |
| PCSA 1 | 0.35 | 446 | 3.52 | 5.29 |
| PCSA 2 | 0.35 | 446 | 5.59 | 6.42 |
| CAC1 OPC2 | 0.35 | 446 | 4.87 | 8.03 |
| CSA1 OPC2 | 0.35 | 446 | 2.53 | 5.83 |

Table 16. Splitting tensile strength in Mpa at 390 kg/m$^3$ cement binder.

| Cement ID | w/c ratio | Cement Binder (kg/m3) | Age | |
|---|---|---|---|---|
| | | | **1d** | **28d** |
| CAC 1 | 0.35 | 390 | 1.53 | 6.24 |
| CSA 1 | 0.35 | 390 | 5.89 | 5.76 |
| CSA 2 | 0.35 | 390 | 4.09 | 3.44 |
| CAC1 B1 | 0.35 | 390 | 4.51 | 8.32 |
| CSA2 B1 | 0.35 | 390 | 7.73 | 6.58 |
| CSA2 B2 | 0.35 | 390 | 4.93 | 6.04 |
| PCSA 1 | 0.35 | 390 | 3.63 | 7.7 |
| PCSA 2 | 0.35 | 390 | 1.53 | 3.57 |
| CAC1 OPC2 | 0.35 | 390 | 0.81 | 8.4 |
| CSA1 OPC2 | 0.35 | 390 | 4 | 7.67 |

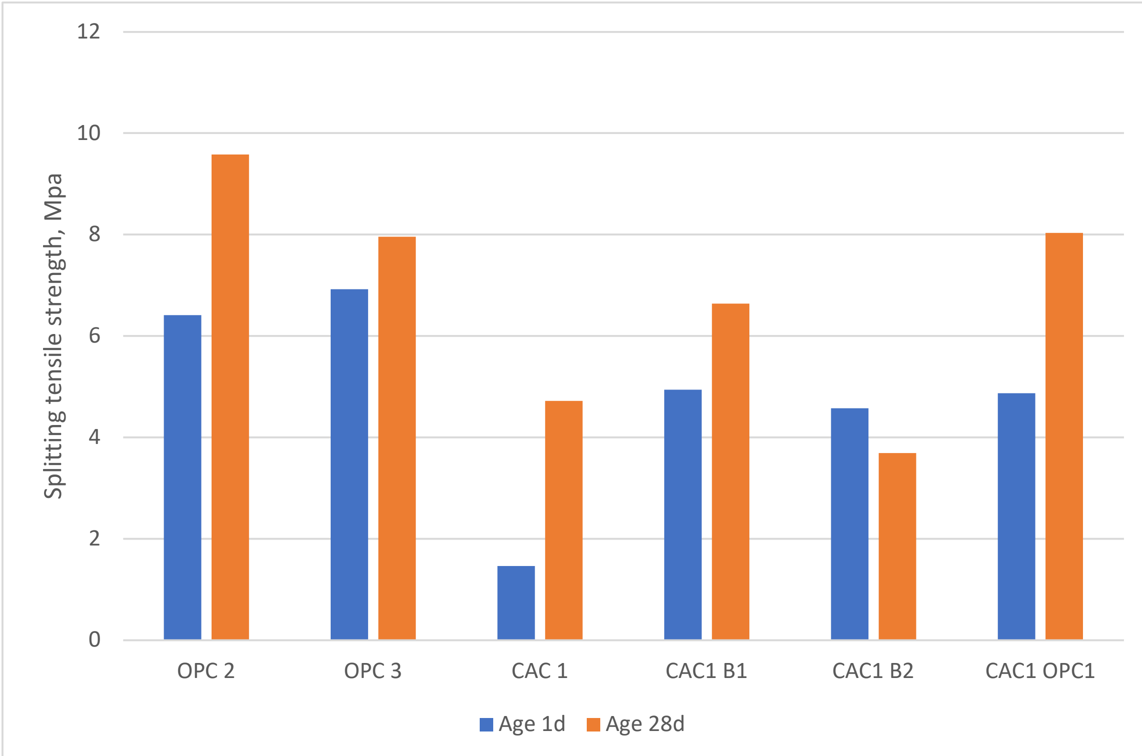


Fig. 13 Splitting tensile strength of OPC 2, 3, CAC cement at 446 kg/m$^3$ cement binder.

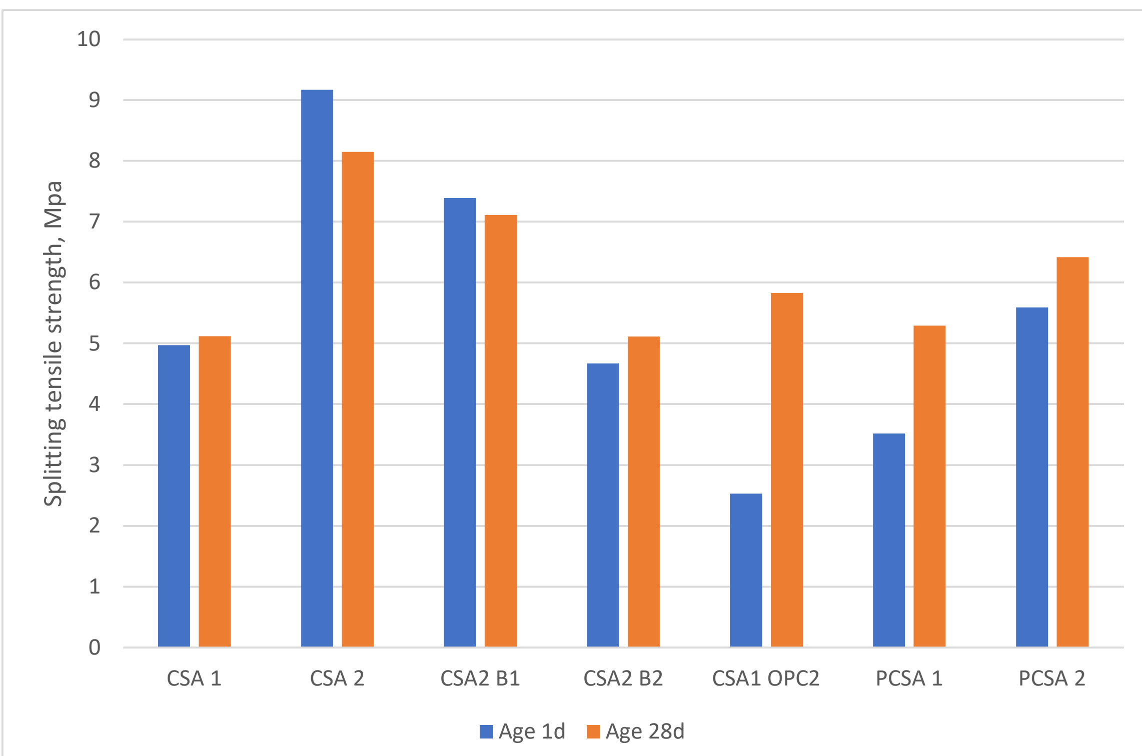


Fig. 14 Splitting tensile strength of CSA cement at 446 kg/m$^3$ cement binder.

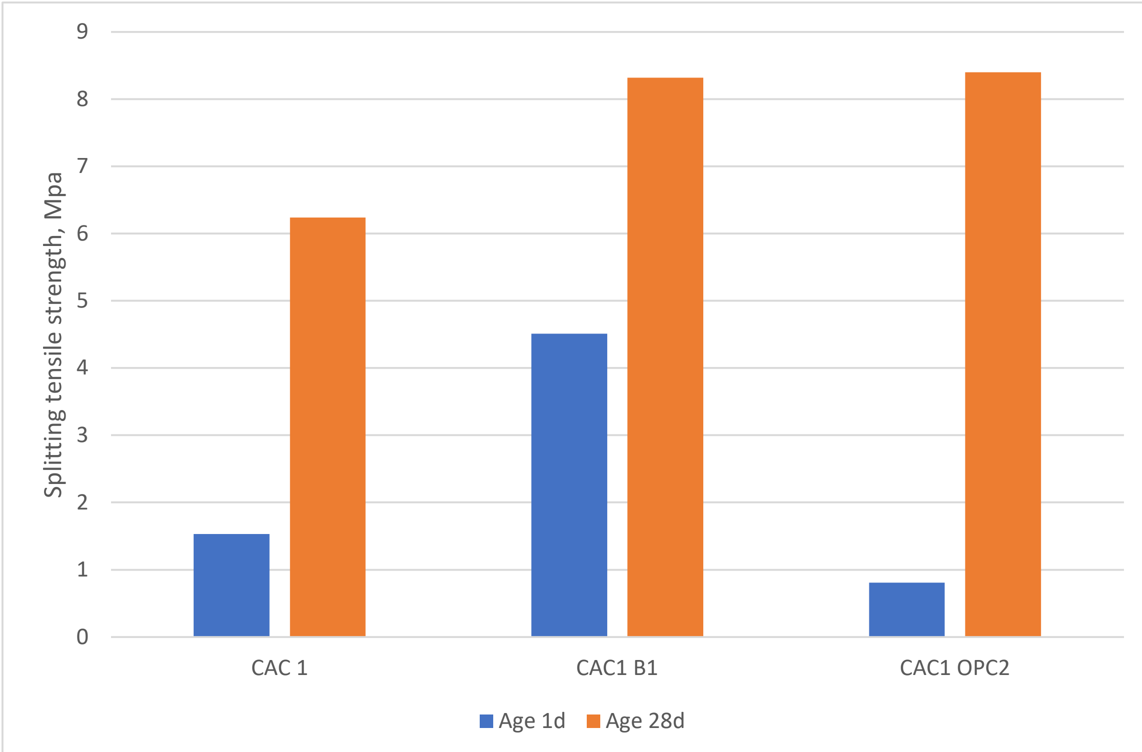


Fig. 15 Splitting tensile strength of CAC cement at 390 kg/m$^3$ cement binder.

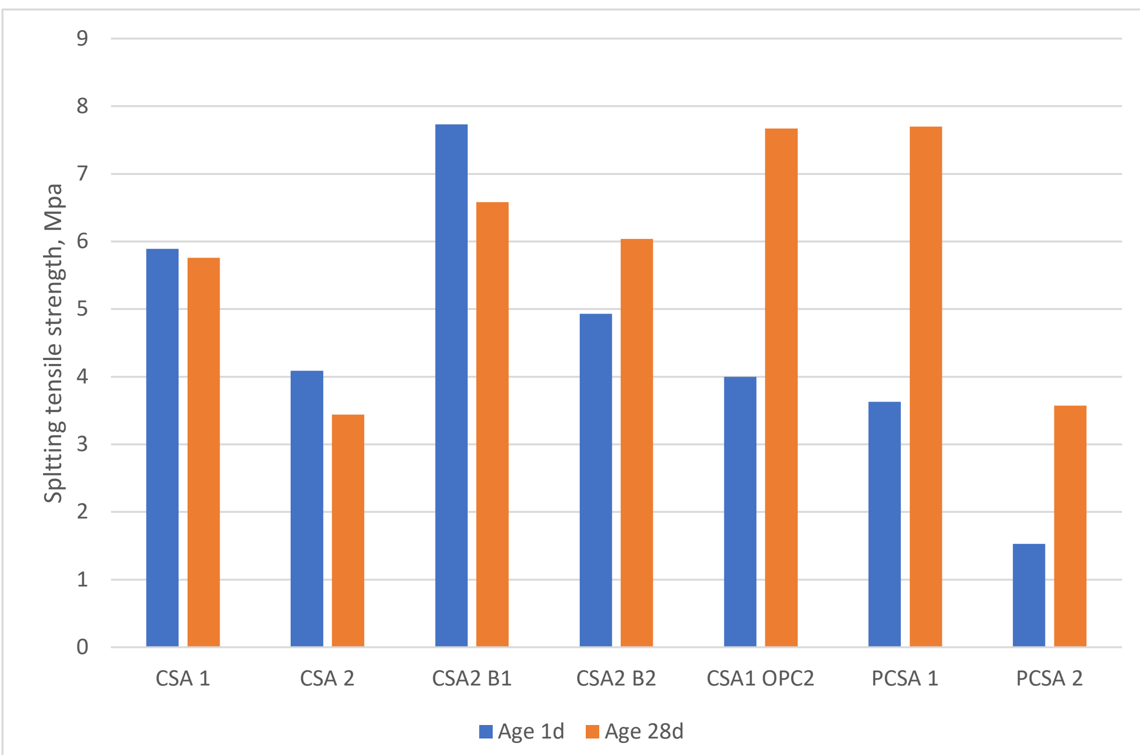


Fig. 16 Splitting tensile strength of CSA cement at 390 kg/m$^3$ cement binder.

Fig. 13 and 14 represent splitting tensile strength data for OPC 2, OPC 3, CAC, and CSA cement at 446 kg/m$^3$ cement binder. Whereas fig. 15 and 16 represent splitting tensile strength results of CAC and CSA cement at 390 kg/m$^3$ cement binder. CAC cement mixtures tend to have more splitting tensile strength at 390 kg/m$^3$ cement binder at age 28d. At 1d splitting tensile strength of CAC cement is almost identical for 446 and 390 kg/m$^3$, whereas for lab blended CAC cement at 446 kg/m$^3$ cement binder has tensile strength of around 4.5 Mpa. Straight cement CSA 1, CSA 2, and proprietary cement CSA2 B1 reduce tensile strength from 1d to 28d at 446 and 390 kg/m$^3$ cement binder. Lab blended CSA1 OPC2 at 390 kg/m$^3$ cement binder has a splitting tensile strength of more than 7.5 Mpa at 28d age. PCSA1 and PCSA2 have splitting tensile strength less than 6.5 Mpa at 446 kg/m$^3$ cement binder even at age 28d, but at 390 kg/m$^3$ cement binder PCSA1 has a good splitting tensile strength of more than 7.5 Mpa whereas PCSA2 have less than 4 Mpa at 28d age.

### 4.2.3 Elastic modulus

Firstly, the modulus of elasticity was planned to measure at 1d and 28d age. But, due to unsucessful attempt of samples, the decision was taken rather do it at 7d and 28d. Tables 17 and 18 represents the modulus of elasiticy data in Gpa at cement binder of 446 and 390 kg/m$^3$ at 7d and 28d age, respectively. Few samples were failed to test due to improper sulfur caping of cylindrical concrete specimens. Failing occurs if plane surface is not perpendicular to the specimen axis and causes uneven disribution of load on specimen.

Table 17. Modulus of elasticity results in Gpa at 446 kg/m$^3$ cement binder.

| Cement ID | w/c ratio | Cement Binder (kg/m3) | Age | |
|---|---|---|---|---|
| | | | 7d | 28d |
| OPC 2 | 0.35 | 446 | 35.33 (1d) | |
| CAC 1 | 0.35 | 446 | 36.27 | 39.71 |
| CSA 1 | 0.35 | 446 | 39.77 | 40.04 |
| CSA 2 | 0.35 | 446 | 57.59 | 46.02 |
| CAC1 B1 | 0.35 | 446 | 36.43 | 40.61 |
| CAC1 B2 | 0.32 | 446 | 53.64 | 37.66 |
| CSA2 B1 | 0.35 | 446 | | 49.1 |
| CSA2 B2 | 0.35 | 446 | 42.05 | 39.67 |
| PCSA 1 | 0.35 | 446 | 36 | |
| PCSA 2 | 0.35 | 446 | 35.49 | |
| CAC1 OPC2 | 0.35 | 446 | 37.91 | 41.29 |
| CSA1 OPC2 | 0.35 | 446 | 32.67 | 39.45 |

Table 18. Modulus of elasticity results in Gpa at 390 kg/m$^3$ cement binder.

| Cement ID | w/c ratio | Cement Binder (kg/m3) | Age | |
|---|---|---|---|---|
| | | | 7d | 28d |
| CAC 1 | 0.35 | 390 | 39.78 | 44.52 |
| CSA 1 | 0.35 | 390 | 40.11 | 42.81 |
| CSA 2 | 0.35 | 390 | 39.94 | 40.58 |
| CAC1 B1 | 0.35 | 390 | 35.01 | 46.88 |
| CSA2 B1 | 0.35 | 390 | 40.71 | 44.51 |
| CSA2 B2 | 0.35 | 390 | 41.04 | 45.38 |
| PCSA 1 | 0.35 | 390 | | 40.85 |
| PCSA 2 | 0.35 | 390 | | 43.16 |
| CAC1 OPC2 | 0.35 | 390 | 30.81 | 37.95 |
| CSA1 OPC2 | 0.35 | 390 | 14.95 | 39.37 |

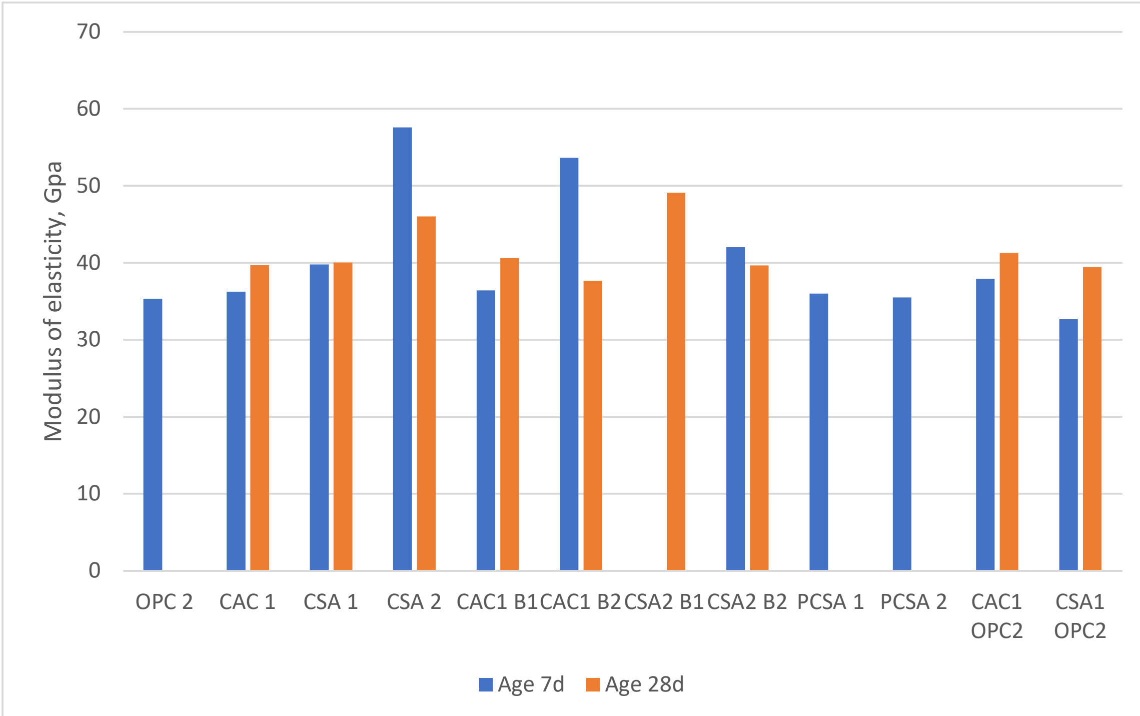


Fig. 17 Modulus of elasticity for concrete mixtures at 446 kg/m$^3$ cement binder.

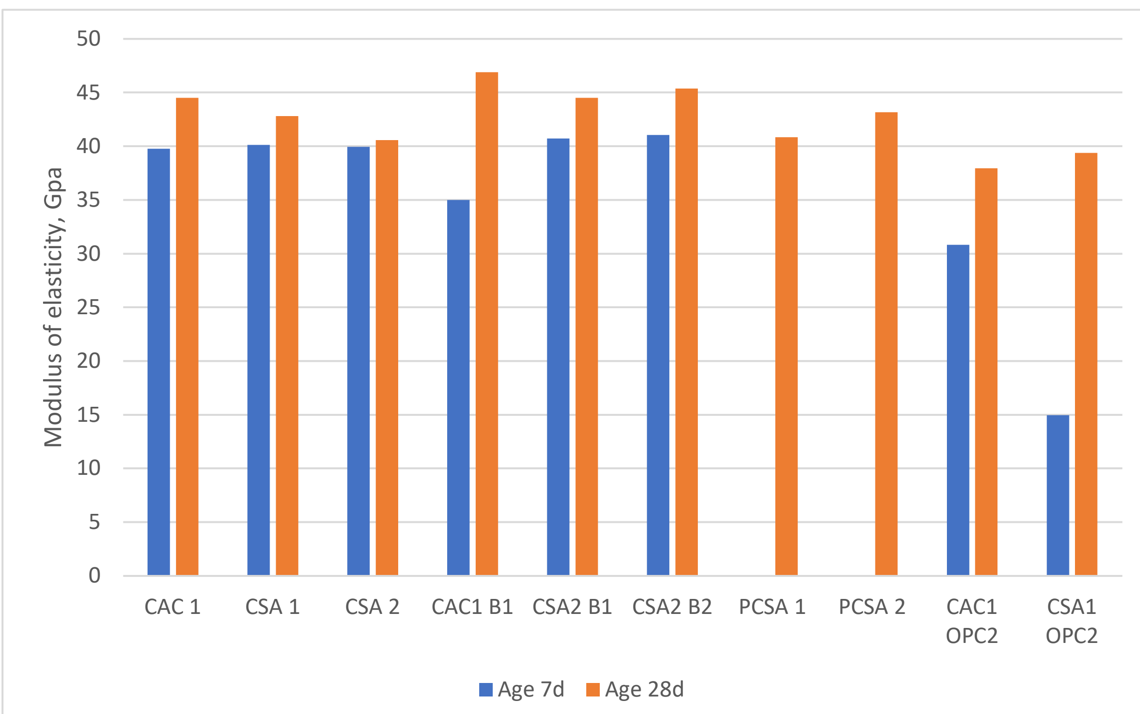


Fig. 18 Modulus of elasticity for concrete mixtures at 390 kg/m$^3$ cement binder.

Fig. 17 shows the graphical representation of modulus of elasticity of cylindrical concrete specimen with cement binder of 446 $kg/m^3$ at age 7d and 28d. Similarly, fig. 18 shows the graphical representation of modulus of elasticity of samples at 390 $kg/m^3$ cement binder. All mixture ID in fig. 17 have elastic modulus more than 35 Gpa at 7d and more than 40 Gpa at 28d. CSA 2, CAC1 B2 and CSA2 B2 elastic modulus reduces from 7d to 28d, rest all cement ID as increase in modulus of elasticity. CSA 2 and CAC1 B2 has more than 55 Gpa elastic modulus at 7d age. All mixture ID in fig. 18 has increase in elastic modulus from age 7d to 28d. No cement ID shows more than 45 Gpa modulus of elasticity even at 28d age with 390 $kg/m^3$ cement binder but has more than 35 Gpa elastic modulus even at age 7d except lab blended cement mixture.

Straight cements CAC 1, CSA 1 and CSA 2 have elastic modulus of around 40 Gpa at age 7d and 28d, except CSA 2 shows more than 55 Gpa elastic modulus at 446 $kg/m^3$ cement binder. Proprietary cement at 446 $kg/m^3$ cement binder shows reduction in elastic modulus from age 7d to 28d. Proprietary CAC cement tends to have more elastic modulus at 390 $kg/m^3$ cement binder, whereas CSA cement has more elastic modulus at 446 $kg/m^3$ cement binder. Lab blended concrete samples aquires better modulus of elasticity at 446 $kg/m^3$ cement binder.

### 4.2.4 Drying shrinkage

The drying shrinkage results for all the concrete prism prepared from Tables 3 and 4, at cement binder of 446 and 390 kg/m$^3$ are listed in Tables 19 and 20, respectively. Initial readings of prism were taken at 6h and 1d, right after demolding them and transferring them into an environmental chamber.

Table 19. Drying shrinkage results for mixture at 446 kg/m$^3$ cement binder.

| Cement ID | Demolded | Shrinkage (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 4d | 7d | 28d | 56d | 112d | 224d |
| OPC 2 | 6h | -0.024 | -0.028 | -0.046 | | -0.049 | -0.035 |
| | 1d | -0.027 | -0.035 | -0.064 | | -0.086 | -0.090 |
| OPC 3 | 6h | | | -0.052 | -0.054 | -0.058 | -0.064 |
| | 1d | | -0.025 | -0.051 | -0.057 | -0.048 | -0.063 |
| CAC 1 | 6h | -0.008 | -0.021 | -0.042 | -0.048 | -0.05 | -0.06 |
| | 1d | -0.031 | -0.041 | -0.035 | -0.056 | -0.060 | -0.070 |
| CSA 1 | 6h | -0.022 | | -0.028 | -0.040 | -0.045 | -0.046 |
| | 1d | 0.005 | | -0.029 | -0.019 | -0.034 | -0.034 |
| CSA 2 | 6h | -0.058 | -0.057 | -0.062 | -0.066 | | -0.076 |
| | 1d | 0.003 | 0.002 | -0.001 | -0.007 | | -0.016 |
| CAC1 B1 | 6h | -0.007 | -0.01 | | -0.016 | -0.036 | -0.036 |
| | 1d | -0.012 | -0.013 | | -0.048 | -0.062 | -0.064 |
| CAC1 B2 | 6h | -0.069 | -0.08 | -0.037 | -0.111 | -0.113 | -0.125 |
| | 1d | -0.034 | -0.049 | | -0.076 | -0.082 | -0.095 |
| CSA2 B1 | 6h | -0.054 | -0.053 | -0.057 | -0.06 | | -0.07 |
| | 1d | 0.005 | 0.004 | 0.001 | -0.004 | | -0.009 |
| CSA2 B2 | 6h | -0.019 | -0.015 | -0.016 | -0.021 | -0.028 | -0.033 |
| | 1d | -0.004 | -0.007 | -0.007 | -0.014 | -0.018 | -0.024 |
| PCSA1 | 6h | -0.024 | -0.025 | -0.053 | | | -0.047 |
| | 1d | -0.007 | -0.029 | -0.062 | | -0.086 | -0.095 |
| PCSA2 | 6h | -0.003 | -0.01 | -0.013 | | -0.025 | -0.026 |
| | 1d | 0.001 | -0.006 | -0.009 | | -0.020 | -0.020 |
| CAC1 OPC2 | 6h | -0.011 | -0.005 | | -0.022 | -0.038 | -0.038 |
| | 1d | -0.011 | -0.020 | | -0.063 | -0.087 | -0.090 |
| CSA1 OPC2 | 6h | -0.010 | -0.010 | -0.018 | | -0.022 | -0.023 |
| | 1d | 0.020 | | 0.019 | 0.029 | 0.016 | 0.017 |

Table 20. Drying shrinkage results for mixture at 390 kg/$m^3$ cement binder.

| Cement ID | Demolded | Shrinkage (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 4d | 7d | 28d | 56d | 112d | 224d |
| CAC 1 | 6h | -0.038 | -0.041 | -0.049 | | -0.062 | -0.064 |
| | 1d | 0.018 | -0.010 | -0.010 | | -0.011 | -0.016 |
| CSA 1 | 6h | -0.016 | -0.02 | -0.029 | -0.032 | -0.037 | -0.036 |
| | 1d | -0.01 | -0.015 | -0.024 | -0.026 | -0.031 | -0.032 |
| CSA 2 | 6h | -0.011 | -0.014 | -0.017 | -0.018 | -0.027 | -0.027 |
| | 1d | -0.007 | -0.007 | -0.011 | -0.012 | -0.024 | -0.020 |
| CAC1 B1 | 6h | -0.019 | -0.033 | -0.180 | -0.145 | -0.115 | -0.119 |
| | 1d | -0.042 | -0.065 | | -0.120 | -0.137 | -0.141 |
| CSA2 B1 | 6h | -0.009 | -0.012 | -0.014 | -0.012 | -0.026 | -0.026 |
| | 1d | -0.008 | -0.009 | -0.012 | -0.014 | -0.023 | -0.024 |
| CSA2 B2 | 6h | -0.007 | -0.008 | -0.011 | -0.010 | -0.020 | -0.020 |
| | 1d | -0.010 | -0.011 | -0.015 | -0.016 | -0.026 | -0.026 |
| PCSA1 | 6h | -0.016 | -0.021 | -0.040 | -0.049 | -0.065 | -0.068 |
| | 1d | -0.018 | -0.025 | -0.051 | -0.062 | -0.080 | -0.084 |
| PCSA2 | 6h | -0.007 | -0.008 | -0.009 | -0.011 | -0.019 | -0.018 |
| | 1d | -0.003 | -0.005 | -0.010 | -0.012 | -0.016 | -0.017 |
| CAC1 OPC2 | 6h | -0.003 | -0.009 | | -0.050 | -0.020 | -0.019 |
| | 1d | -0.001 | -0.006 | -0.010 | -0.015 | -0.019 | -0.020 |
| CSA1 OPC2 | 6h | -0.015 | -0.034 | -0.068 | -0.073 | -0.088 | -0.092 |
| | 1d | -0.005 | -0.027 | -0.068 | -0.079 | -0.095 | -0.099 |

Fig. 19 and 20 represents graphical analytics of the drying shrinkage percentage of all the samples prepared at 446 kg/$m^3$ cement binder: Fig. 19 shows the shrinkage of a prism cured for 6h and whose initial reading was noted at 6h, whereas Fig. 20 shows the shrinkage of a prism cured for 1d and whose initial reading was noted at 1d. Similarly, fig. 21 and 22 represent the drying shrinkage percentage of all the prisms prepared at 390 kg/$m^3$ cement binder.

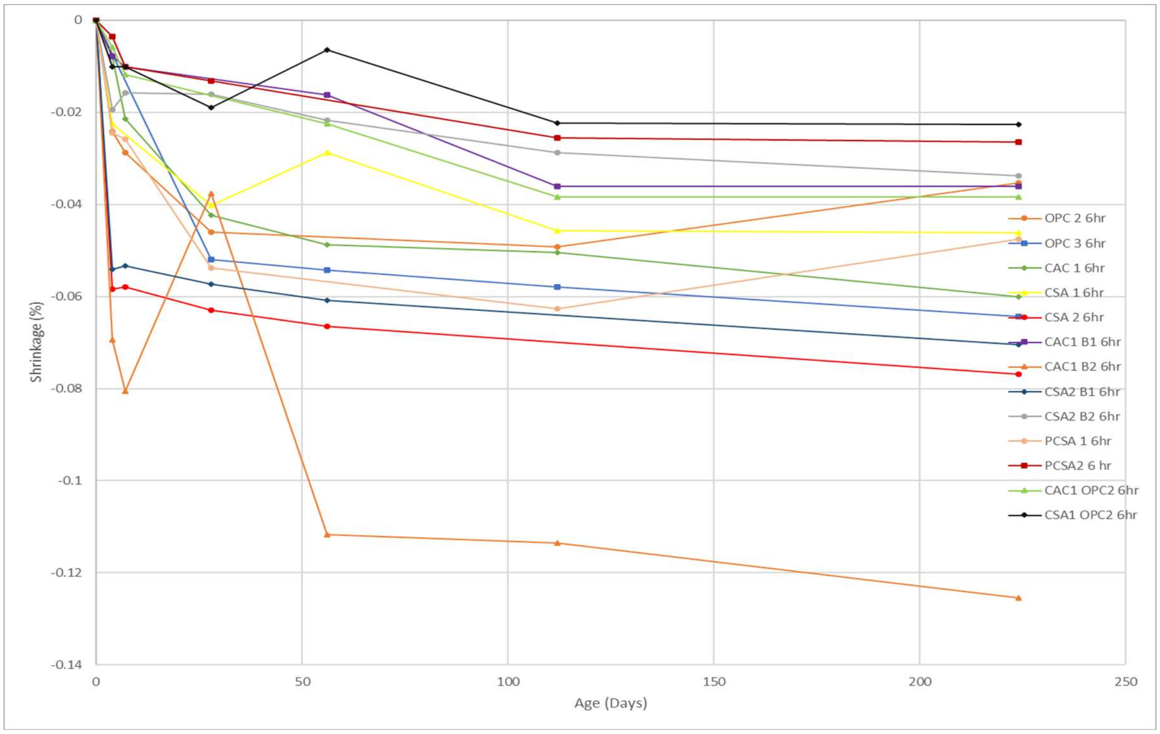


Fig. 19 Drying shrinkage of prism demolded at 6h at 446 kg/m$^3$ cement binder.

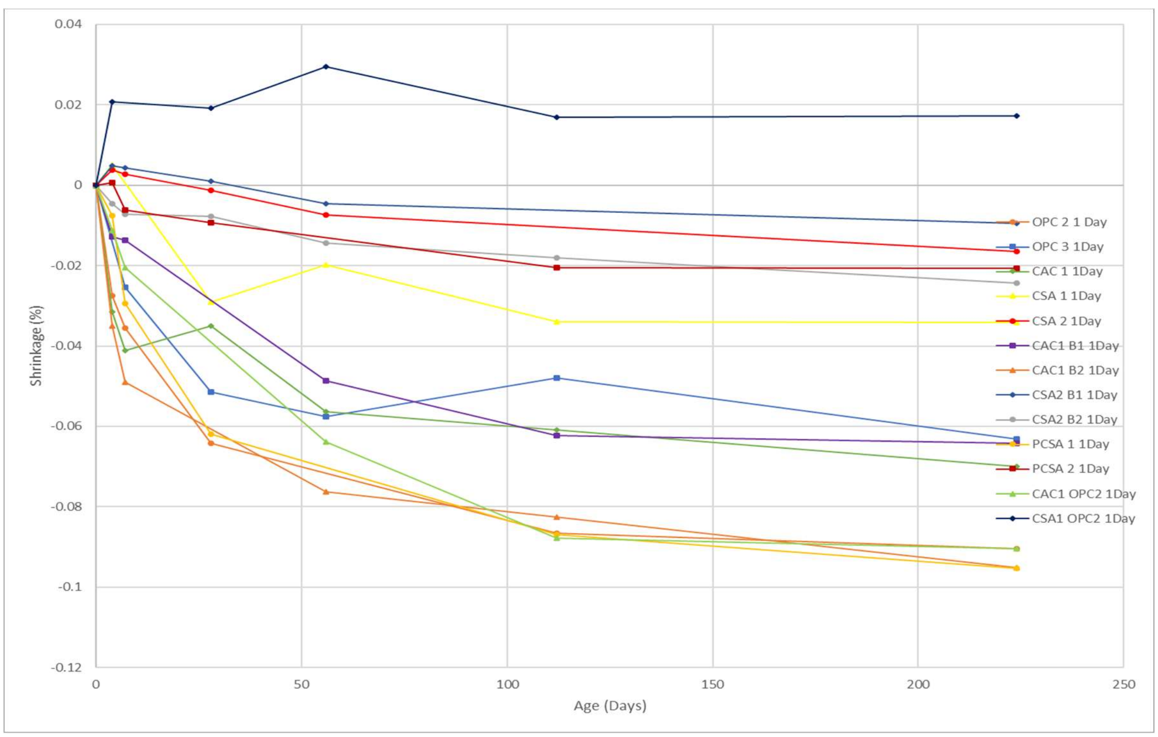


Fig. 20 Drying shrinkage of prism demolded at 1d at 446 kg/m$^3$ cement binder.

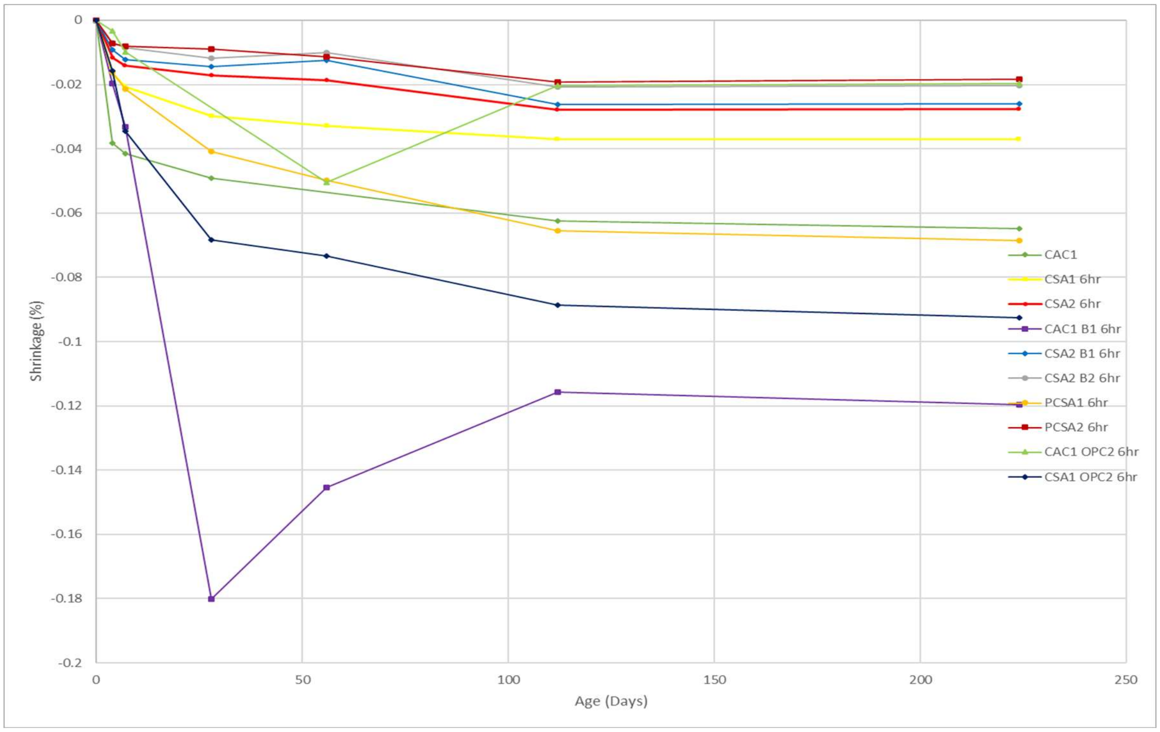


Fig. 21 Drying shrinkage of prism demolded at 6h at 390 kg/m$^3$ cement binder.

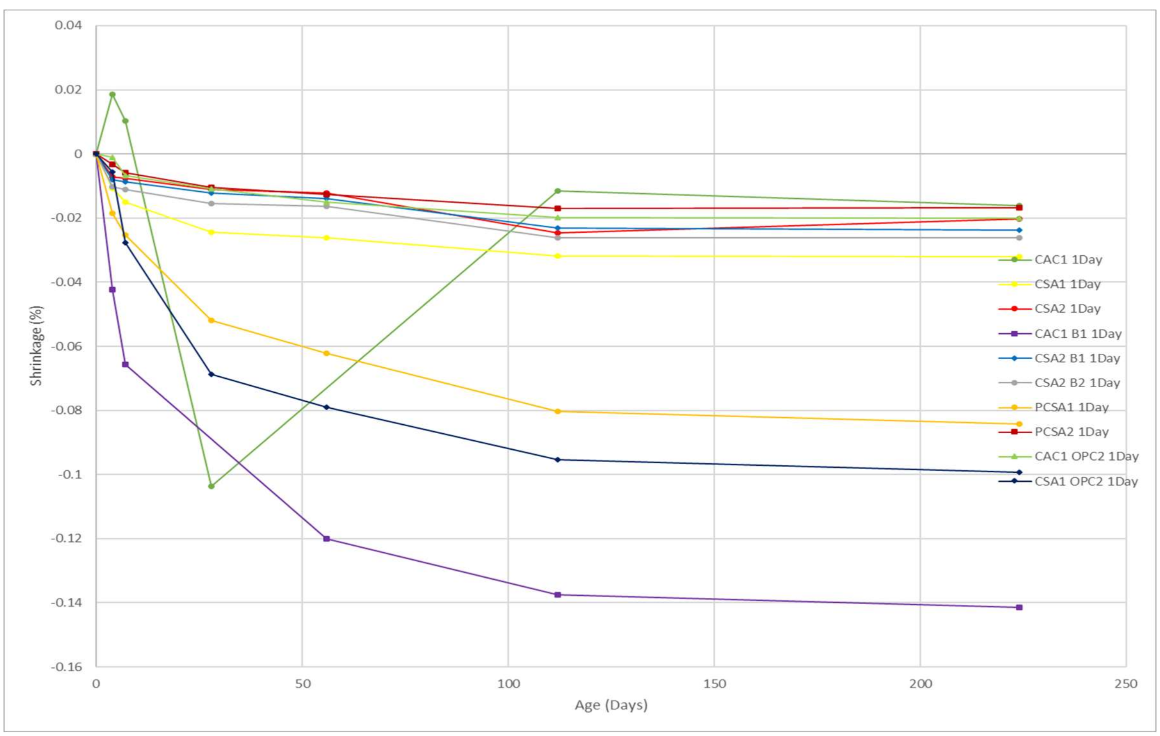


Fig. 22 Drying shrinkage of prism demolded at 1d at 390 kg/m$^3$ cement binder.

The OPC2 and OPC3 are set as base parameters to compare drying shrinkage change in different rapid-setting concrete prisms. The OPC2 prisms demolded at 6h has lesser shrinkage compared to those demolded at 1d. Straight cement CSA1 shrinks less than CSA2 if demolded at 6h, and CSA2 shows significantly less shrinkage when demolded at 1d. Proprietary cement CAC1 B2 shows extreme shrinkage compared to all others when demolded at 6h. PCSA1 cement shows shrinkage reduction, high expansion and agin shrink, when demolded at 6h. Lab blended cement CSA1 OPC2 shows shrinkage when demolded at 6h but expansion when demolded at 1d. CSA-based cement prepared at 446 kg/m3 cement binder shows less drying shrinkage when demolded at 1d. In contrast, CAC-based cement shows more drying shrinkage when demolded at 1d.

Straight cement sample with 390 $kg/m^3$ cement binder has less shrinkage than those made at 446 kg/m3 cement binder. Proprietary cement CAC1 B1 shows extreme shrinkage at both demolded at 6h and 1d. PCSA1 shows more shrinkage when demolded at 1d. Lab blended cement CAC1 OPC2 shows lesser shrinkage when demolded at 6h, CSA1 OPC2 shows almost identical drying shrinkage whether demolded at 6h or 1d.

# 5. CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

1. Slump, unit weight, and air content of different CAC, CSA, and blends containing CAC or CSA with OPC type I/II were determined.
2. The straight and proprietary CAC cement mixture with 390 kg/m3 cement binder sets faster than 446 kg/m3 cement binder. In contrast, the CSA cement mixture has a faster setting time, observed at 446 kg/m3 cement binder. The setting time properties were opposite for the lab blended cement 25% of CAC or CSA mixed with 75% OPC type I/II. The faster setting time occurred for CAC OPC at 446 kg/m3 and CSA OPC at 390 kg/m3 cement binder.
3. The amount of sulfite is directly proportional, and the amount of aluminum oxide and iron oxide is inversely proportional to the early age gain in compressive strength. CSA cement is rich in sulfite content but significantly less aluminum and iron oxide, showing higher compressive strength at an early age at 446 $kg/m^3$ cement binder. CAC contains a low amount of sulfite, but a higher composition of aluminum and iron oxide hence shows a delay in compressive strength with early ages.
4. The calcium content in OPC type I/II and OPC type III is highest than all other cement types. It hence achieves the highest compressive strength at a later age of 91d compared to other cement-type concrete mixtures.
5. Higher the amount of CSA and lower the amount of CAC faster is the rapid strength gain at an early age. Therefore, CSA at 446 kg/m3 cement binder and CAC at 390 kg/m3 cement binder can meet the expectation of rapid setting concrete depending on the application of concrete.

6. CAC and CSA cement have better tensile strength at 390 kg/m3 cement binder, except straight cement CSA2 and PCSA2 show higher tensile strength at 446 kg/m3 cement binder.
7. Modulus of elasticity results for all CAC, CSA, and blends containing CAC or CSA with OPC type I/II at age 1d and 28d are revealed.
8. The drying shrinkage of the concrete prisms cured, and an initial reading taken at 6h, and 1d for all CAC, CSA, and blends containing CAC or CSA with OPC type I/II at cement binder of 446 and 390 kg/m3 with w/c ratio 0.35 is represented graphically.

## 5.2 Future Work

The compressive strength of all cylindrical concrete specimen for all cement ID at later age (long-term) of 365d is to be determined. The prisms stored in an environmental chamber will be monitored at 448d for all concrete mixture in Table 3 and 4. Long-term hardened properties data will help in better understanding of RSHCs. With the use of fresh and hard properties knowledge of rapid setting hydraulic cement and further studies like durability; the CSA, CAC or blends will be prepared for use depending on requirement of application.

## REFERENCES CITED

Akthem A. Al-Manaseer, E. B. A., & Hasan, K. Properties of Concrete Containing Ultimax Rapid- Setting Hydraulic Cement. *ACI Materials Journal, 96*(5). doi:10.14359/654

Al Horr, Y., Elhoweris, A., & Elsarrag, E. (2017). The development of a novel process for the production of calcium sulfoaluminate. *International Journal of Sustainable Built Environment, 6*(2), 734-741.

Bentivegna, A. F. (2012). *Multi-scale characterization, implementation, and monitoring of calcium aluminate cement based-systems.*

Bescher, E., & Kim, J. (2019). *Belitic Calcium Sulfoaluminate Cement: History, Chemistry, Performance, and Use in the United States.* Paper presented at the 1st International Conference on Innovation in Low-Carbon Cement and Concrete Technology, London, UK.

Biolzi, L., Cattaneo, S., Guerrini, G., & Afroughsabet, V. (2020). Sustainable concretes for structural applications. In *Regeneration of the Built Environment from a Circular Economy Perspective* (pp. 249-261): Springer, Cham.

Coppola, L., Coffetti, D., Crotti, E., & Pastore, T. (2018). CSA-based Portland-free binders to manufacture sustainable concretes for jointless slabs on ground. *Construction and Building Materials, 187*, 691-698.

Fowler, D. W., & Whitney, D. P. (2011). *Long-term performance of polymer concrete for bridge decks* (Vol. 423): Transportation Research Board.

Gartner, E. (2004). Industrially interesting approaches to "low-CO2" cements. *Cement and concrete research, 34*(9), 1489-1498.

Gosselin, C., Gallucci, E., & Scrivener, K. (2010). Influence of self heating and Li2SO4 addition on the microstructural development of calcium aluminate cement. *Cement and concrete research, 40*(10), 1555-1570.

Gu, P., Beaudoin, J. J., Quinn, E. G., & Myers, R. E. (1997). Early strength development and hydration of ordinary Portland cement/calcium aluminate cement pastes. *Advanced cement based materials, 6*(2), 53-58.

Habert, G. (2014). Assessing the environmental impact of conventional and 'green'cement production. In *Eco-efficient Construction and Building Materials* (pp. 199-238): Elsevier.

Harrison, T., Jones, M. R., & Lawrence, D. (2019). The Production of Low Energy Cements. *Lea's Chemistry of Cement and Concrete*, 341.

Hidalgo Lopez, A., García Calvo, J. L., García Olmo, J., Petit, S., & Alonso, M. C. (2008). Microstructural evolution of calcium aluminate cements hydration with silica fume and fly ash additions by scanning electron microscopy, and mid and near-infrared spectroscopy. *Journal of the American Ceramic Society, 91*(4), 1258-1265.

Ioannou, S., Paine, K., Reig, L., & Quillin, K. (2015). Performance characteristics of concrete based on a ternary calcium sulfoaluminate–anhydrite–fly ash cement. *Cement and Concrete Composites, 55*, 196-204.

Juenger, M., Winnefeld, F., Provis, J. L., & Ideker, J. (2011). Advances in alternative cementitious binders. *Cement and concrete research, 41*(12), 1232-1243.

Kastiukas, G., Zhou, X., Castro-Gomes, J., Huang, S., & Saafi, M. (2015). Effects of lactic and citric acid on early-age engineering properties of Portland/calcium aluminate blended cements. *Construction and Building Materials, 101*, 389-395.

Khayat, K. H., & Assaad, J. (2002). Air-void stability in self-consolidating concrete. *ACI Materials Journal, 99*(4), 408-416.

Kitamura, M., Kamitani, M., & Senna, M. (2000). Rapid hardening of cement by the addition of a mechanically activated Al (OH) 3–Ca (OH) 2 mixture. *Journal of the American Ceramic Society, 83*(3), 523-528.

Kosmatka, S. H., Kerkhoff, B., & Panarese, W. C. (2002). *Design and control of concrete mixtures* (Vol. 5420): Portland Cement Association Skokie, IL.

Kumar, R. (2016). A review on epoxy and polyester based polymer concrete and exploration of Polyfurfuryl Alcohol as polymer concrete. *Journal of Polymers, 2016*.

Leung, C. K., & Pheeraphan, T. (1995). Microwave curing of Portland cement concrete: experimental results and feasibility for practical applications. *Construction and Building Materials, 9*(2), 67-73.

Li, P., Gao, X., Wang, K., Tam, V. W., & Li, W. (2020). Hydration mechanism and early frost resistance of calcium sulfoaluminate cement concrete. *Construction and Building Materials, 239*, 117862.

Macadam, D., Smith, K., Fowler, D. W., & Meyer, A. (1984). Evaluation of rapid-setting concrete. *Transportation Research Record, 1003*, 19-27.

Mangabhai, R. (1990). *Calcium Aluminate Cements: Proceedings of a Symposium dedicated to HG Midgley, London, July 1990*: CRC Press.

Nodehi, M. (2021). Epoxy, polyester and vinyl ester-based polymer concrete: a review. *Innov Infrastruct Solut, 6*, 1-20.

Nodehi, M., & Aguayo, F. (2021). Ultra high performance and high strength geopolymer concrete. *Journal of Building Pathology and Rehabilitation, 6*(1), 1-29.

Nodehi, M., & Taghvaee, V. M. (2021). Alkali-activated materials and geopolymer: a review of common precursors and activators addressing circular economy. *Circular Economy and Sustainability*, 1-32.

Péra, J., & Ambroise, J. (2004). New applications of calcium sulfoaluminate cement. *Cement and concrete research, 34*(4), 671-676.

Pimraksa, K., & Chindaprasirt, P. (2018). Sulfoaluminate cement-based concrete. In *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures* (pp. 355-385): Elsevier.

Qin, L., Gao, X., & Zhang, A. (2018). Potential application of Portland cement-calcium sulfoaluminate cement blends to avoid early age frost damage. *Construction and Building Materials, 190*, 363-372.

Reis, J. M. L. d. (2012). Effect of temperature on the mechanical properties of polymer mortars. *Materials Research, 15*(4), 645-649.

Schmidt, M., Fehling, E., Glotzbach, C., Here, I. N., Fröhlich, S., & Piotrowski, S. (2012). *Ultra-High Performance Concrete and Nanotechnology in Construction. Proceedings of Hipermat 2012. 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials*: Kassel University Press.

Scrivener, K., & Capmas, A. (2003). Calcium aluminate cements. *Advanced concrete technology, 3*, 1-31.

Scrivener, K. L., Cabiron, J.-L., & Letourneux, R. (1999). High-performance concretes from calcium aluminate cements. *Cement and concrete research, 29*(8), 1215-1223.

Shi, C., Zou, X., & Wang, P. (2020). Influences of EVA and methylcellulose on mechanical properties of Portland cement-calcium aluminate cement-gypsum ternary repair mortar. *Construction and Building Materials, 241*, 118035.

Tambara Jr, L., Cheriaf, M., Rocha, J., Palomo, A., & Fernández-Jiménez, A. (2020). Effect of alkalis content on calcium sulfoaluminate (CSA) cement hydration. *Cement and concrete research, 128*, 105953.

Torréns-Martín, D., Fernández-Carrasco, L., & Blanco-Varela, M. T. (2013). Conduction calorimetric studies of ternary binders based on Portland cement, calcium aluminate cement and calcium sulphate. *Journal of thermal analysis and calorimetry, 114*(2), 799-807.

Trauchessec, R., Mechling, J.-M., Lecomte, A., Roux, A., & Le Rolland, B. (2015). Hydration of ordinary Portland cement and calcium sulfoaluminate cement blends. *Cement and Concrete Composites, 56*, 106-114.

Xu, Q., Ji, T., Yang, Z., & Ye, Y. (2019). Preliminary investigation of artificial reef concrete with sulphoaluminate cement, marine sand and sea water. *Construction and Building Materials, 211*, 837-846.

Zhang, J., Li, G., Yang, X., Ren, S., & Song, Z. (2018). Study on a high strength ternary blend containing calcium sulfoaluminate cement/calcium aluminate cement/ordinary Portland cement. *Construction and Building Materials, 191*, 544-553.

Zhang, Y., Ye, G., Gu, W., Ding, D., Chen, L., & Zhu, L. (2018). Conversion of calcium aluminate cement hydrates at 60° C with and without water. *Journal of the American Ceramic Society, 101*(7), 2712-2717.

Zhou, Q., Milestone, N., & Hayes, M. (2006). An alternative to Portland cement for waste encapsulation—the calcium sulfoaluminate cement system. *Journal of hazardous materials, 136*(1), 120-129.

ASCE's 2021 American Infrastructure Report Card: GPA: C-. (2021, September 13). Retrieved October 14, 2021, from https://infrastructurereportcard.org/.