MITIGATION OF ADDITIONAL OVERDESIGN IN PORTLAND CEMENT CONCRETE BY OPTIMIZING THE CEMENTITIOUS MATERIALS CONTENT

MITIGAÇÃO DO SUPERDIMENSIONAMENTO EXCESSIVO DO CONCRETO PELA OTIMIZAÇÃO DO TEOR DE MATERIAIS CIMENTÍCIOS

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ABSTRACT

More cement does not necessarily make better concrete or expedite construction schedules. In contrast, concrete with lower cementitious content can reach sufficient strength on time to avoid construction delays and last longer. Standard specifications require concrete overdesign (OD) for decades, but studies assessing the actual OD magnitudes are rare. This experimental study aimed to identify the required cementitious materials content (RCC) to meet the OD based on 958 compressive strength tests (σ) representing 8200 m³ of ready-mixed concrete for threshold buildings. The actual OD in commercial concrete appears to be 7 to 21% higher than required. The cementitious materials content should be reduced between 6 and 17% so that concrete can reach the required compressive strength (f'cr) without cement overconsumption. The additional overdesign (AOD) increased significantly as the specified compressive strength (f'c) increased, indicating that concrete producers can be more cautious when the f'cr is higher. Further research is needed to expand the range of cementitious contents and applications.

KEYWORDS

Overconsumption; Portland cement; Concrete; Limestone aggregates; Overdesign; Overstrength; Compressive strength.

RESUMO

Mais cimento não necessariamente melhora a qualidade do concreto ou agiliza os cronogramas de construção. Em contraste, o concreto com menor teor de cimento pode durar mais e atingir resistência suficiente a tempo para evitar atrasos na construção. As normas técnicas exigem o superdimensionamento do concreto por décadas, mas estudos que avaliam as magnitudes do superdimensionamento real são raros. Este estudo experimental teve como objetivo identificar o teor de materiais cimentícios necessário para atender ao superdimensionamento requerido com base em 958 ensaios de resistência à compressão (σ) representando 8200 m³ de concreto para construções comerciais. O superdimensionamento real do concreto parece ser 7 a 21% acima do necessário. O conteúdo de materiais cimentícios deve ser reduzido entre 6 e 17% para que o concreto possa atingir a resistência à compressão requerida (f'cr) sem excesso de cimento. O nível do superdimensionamento excessivo aumentou significativamente com o aumento da resistência à compressão especificada (f'c), indicando que os produtores de concreto parecem ser mais cautelosos quando o f'cr é maior. Pesquisas adicionais são necessárias para expandir a gama de aplicações e teor de materiais cimentícios.

PALAVRAS CHAVE

Teor de cimento; Cimento Portland; Concreto; Agregado calcário; Superdimensionamento; Resistência a compressão.

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1. INTRODUCTION

More cement does not necessarily make stronger concrete or accelerates construction. In contrast, several studies have shown that concrete with lower cementitious content can reach sufficient strength in a brief period of time, avoiding construction delays, and the concrete lasts longer (ACI 2005; ACI 2007; ACI 2016; ACI 2019a; MEHTA AND MONTEIRO, 2006).

Concrete mixtures are typically proportioned following the American Concrete Institute (ACI) standard 211-1 (ACI, 2011) or similar, and the ACI 318 (ACI, 2019a) specifies that concrete should reach a minimum required compressive strength f'_{cr} higher than the specified design compressive strength f'_{c}. The ACI 214R (ACI, 2019b) defines the f'_{cr} as the average compressive strength that will guarantee that only one percent of measurements falls below the f'_{c}. The difference between f'_{cr} and f'_{c} is defined as concrete overdesign (*OD*).

The *OD* calculation is based on the availability of relevant data for similar concrete mixtures. ACI 214R (ACI, 2019b) recommends modification factors for standard deviation (S) from 1.16 when 15 tests are available to 1,0 when 30 or more compressive strength (σ) tests are available. When a concrete mix design has a normal distribution of σ test results, Equation 1 can be used:

$$f'_{cr} = f'_{c} + z\,S, \qquad (1)$$

where f'_{cr} is the required compressive strength of concrete, f'_{c} is the specified compressive strength of concrete, *z* is the reliability factor (typically 2,33 in the U.S. for acceptance of the 1 % failure rate), and S is the standard deviation of a concrete series.

When fewer than 15 σ tests are available, the overdesign determination relies upon the f'_{c} level. In such a case, 7 MPa is added to f'_{c} when f'_{c} is less than 21 MPa, 8 MPa is added to f'_{c} when f'_{c} is greater or equal to 21 MPa and less than or equal to 35 MPa, and Equation 2 should be used when f'_{c} is greater than 35 MPa:

$$f'_{cr} = 1{,}1 \times f'_{c} + 5\ \text{MPa}, \qquad (2)$$

where f'_{cr} is the required compressive strength of concrete and f'_{c} is the specified compressive strength of concrete.

During construction, concrete specimens are cured in moisture rooms or curing tanks with lime water. Typically, after 7 and 28 days of curing, σ is tested and compared to f'_{c} (FDOT, 2020; FDOT, 2021; MEHTA AND MONTEIRO, 2006). Concrete is considered adequate if σ falls above f'_{c}. Because such evaluations are specified in contracts that hold builders and concrete producers liable for concrete failures, efforts are made to keep σ higher than the minimum. The cementitious content in concrete tends to be increased due to the misconception that this practice is the only solution, when the water-to-cementitious ratio (*w/cm*) is widely known as the primary factor that affects concrete strength (MEHTA AND MONTEIRO, 2006). The prevailing, yet flawed, logic behind this is that the higher the *OD*, the lower the risk of obtaining strength results below f'_{c}.

However, the overstrength may result in thermal and shrinkage cracks. This occurs because 1) There is a maximum limit of cement to produce higher strength concrete; 2) Higher concrete temperature can increase the temperature differential between core and ambient; 3) The higher the cementitious content, the higher the heat of hydration, which might lead to delayed ettringite formation (DEF); and 4) For a specified *w/cm*, a rise in cementitious content leads to an increase in water content, which may bleed and evaporate during the curing process resulting in higher porosity and permeability in concrete (ACI 2007; ACI 2016; ACI 2019a; MEHTA AND MONTEIRO, 2006).

Specific contract terms have also induced the increase in f'_{cr} to become the norm in construction by offering bonuses to contractors to expedite construction. The "No Excuse Bonus" terms have encouraged the work acceleration to fit fast-track schedules that have been proposed to minimize inconvenience during construction (e.g., traffic delays). This incentive, very common in building contracts, bonds and rewards a contractor for early completion, but may affect the quality and durability of the constructed element. For example, the use of admixtures to accelerate setting time associated with high contents of fast-reacting cement can induce concrete pathologies (MEHTA AND MONTEIRO, 2006).

For those reasons, this study investigates the actual cementitious materials content in concrete required to meet the *OD*. Although standard guidelines require concrete *OD* for decades, such a threshold can be abused to avoid results below the f'c. This experimental study is carried out for the first time and will be helpful in concrete technology.

1.1. Portland Cement

Portland cement (PC) is the most widely used construction material because it is adaptable, reliable, accessible, and affordable. Over 159 countries manufacture clinker, the prime ingredient in cement. Four billion tons of cement are manufactured each year worldwide. In 2017, the United States (U.S.) was the world's third most significant producer of cement (86 million metric tons), behind India (270 million metric tons) and China (2 billion metric tons). In the U.S., cement is produced at 98 plants in 34 states and two plants in Puerto Rico. Florida accounts for eight large cement plants producing 6 million metric tons of PC and 8 million metric tons of clinker per year (HERBERT, 2007; USGS, 2018).

The PC is the most used construction material on Earth. It is widely known that the cement production process is an energy-intensive and heavy polluter. Due to its substantial environmental impact, the cement industry has intensified its focus on reducing carbon dioxide (CO^2) emissions, which currently accounts for approximately 5 - 10 % globally (AGOPYAN AND JOHN, 2011; KHATIBMASJEDI *et* *al.*, 2016; LE QUÉRÉ, 2015; MEHTA AND MONTEIRO, 2006; TECHNOLOGY ROADMAP, 2018).

Efforts to reduce the environmental footprint include the replacement of inefficient equipment with more environmentally friendly versions, use of renewable fuels, clean energy systems, innovative technologies for CO^2 capture and storage, the production of blended cement, and cement replacement with supplementary cementitious materials such as ground granulated blast furnace slag (GGBFS) and fly ash (FA) (WINTER, 2014). The U.S. producers decreased their use of fossil fuels by over 15%, and the total energy required to produce a ton of cement by 40%. The creation of portland limestone cement (PLC), dubbed Type IL cement, is also part of the industry effort to reduce greenhouse gas (GHG) emissions. PLC is a blended cement that requires a reduced amount of limestone burned in kilns, which decreases CO2 emissions and the total amount of mined limestone. Due to its lower clinker-to-cement ratio, PLC is considered an eco-friendly cement, which has become widely used (ANDREW, 2018; NOËL et al., 2016; WASSERMANN et al., 2016).

Although PLC production can meet global environmental goals, high-cement consumption in concrete remains an issue that can be particularly acute in some regions. South Florida in the U.S. is an intensive producer of cement, limestone aggregates, and concrete. The high-quality limestone produced in the region is used in cement and most concrete production because of its suitable hardness. Thus, although PLC can reduce some of the limestone demand, the potential production of concrete with high cement contents can decrease overpressure on the local deposits and challenge the long-term availability of limestone.

1.2. PLC production

Three plants are currently producing PLC in Florida. Mill certificates from these plants show that the Blaine fineness is 51% higher than the standard fineness of Type I/II cement. Although finer than Type I/II, PLC is expected to produce similar heat during hydration since the Calcium Oxide (CaO) contents are comparable in both cement types. Figure 1 shows the primary limestone formations and regions where cement is produced in Florida.

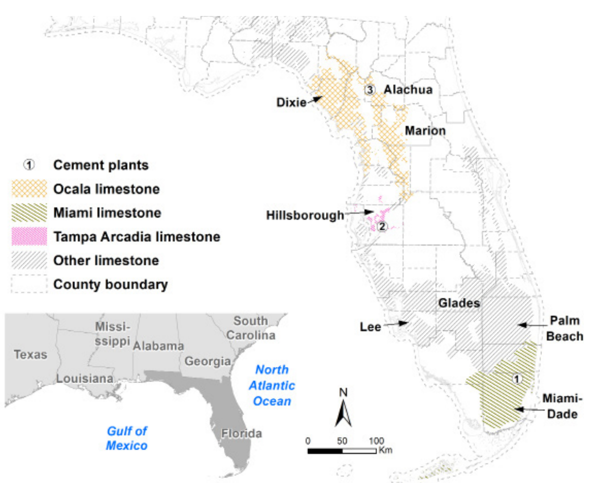

Figure 1: Location of limestone formations and portland limestone cement plants considered in the study area.
Source: Author.

PC is produced by heating limestone, silica, alumina, and iron in kilns at 1500 °C to produce clinker. The clinker passes through ball mills to achieve the target particle size distribution (PSD) and fineness. Afterward, up to 5% of gypsum is blended to control the setting properties, adding sulfate to the cement chemical composition (AGOPYAN AND JOHN, 2011; ANTUNES AND TIA, 2018a; ANTUNES AND TIA, 2018b; MEHTA AND MONTEIRO, 2006). All cement used in commercial construction in the U.S. must be produced conforming to either ASTM C150 (ASTM, 2020a), or C595 (ASTM, 2020b), besides AASHTO M85 (AASHTO, 2020a) for PC and M240 (AASHTO, 2020b) for blended cement for road construction.

PLC differs from PC in its manufacturing process. Although both cement types use similar clinker, PLC can receive up to 15% ground limestone in the finishing mill. Manufacturers claim that this reduces their carbon emission rates without increasing cost or reducing performance. The PSD of PLC is also enhanced and often achieves higher cementitious efficiency (COST, 2013; JIN et al., 2018).

1.3. Limestone mining

Limestone is a sedimentary rock composed of over 50% of carbonate minerals, primarily calcium carbonate ($CaCO^3$). Limestone content in cement is determined by its chemical composition, which varies in purity, consistency, and hardness based on location. PC is one of the most important products made from limestone, comprising at least 70% of $CaCO^3$ by mass in cement production composition (HERBERT, 2007; USGS, 2018).

Florida produces 92% of the in-state demand for limestone. The hardest limestone for aggregate materials occurs in small areas on the Southeast coast (Lake-Belt), which is the source of 95% of the crushed limestone used in concrete statewide. The state has an abundance of soft limestone, typically unsuitable for structural concrete. Figure 2 shows the crushed-stone production in Florida between 2001 and 2015. After the 2008 national economic crisis, limestone mining has increased steadily (HERBERT, 2007).

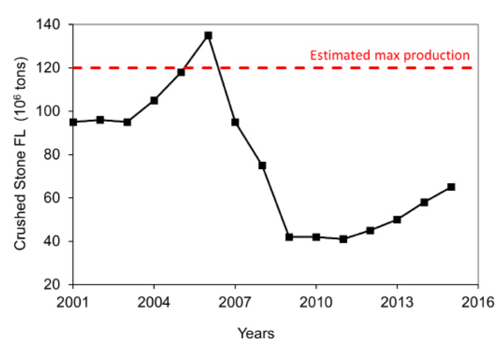

Figure 2: Crushed-stone production in Florida.
Source: Author.

2. RESEARCH SIGNIFICANCE

Although standard guidelines require concrete overdesign for decades, such a threshold can be abused. This experimental study can identify the currently required cementitious materials content in concrete to meet the overdesign based on compressive strength tests. This investigation is carried for the first time and will be particularly useful to concrete technology.

3. CONSTRUCTION MATERIALS

Silica sand will be used as fine aggregate (FA) and limestone grade 57 as coarse aggregate (CA). Figure 3 shows the gradation curve of each aggregate per ASTM C136 (ASTM, 2019a). Table 1 presents the physical properties of the aggregates tested per C127 (ASTM, 2015a), C128 (ASTM, 2015b), and C136 (ASTM, 2019a). Type IL-10 PLC per ASTM C595 (ASTM, 2020b) was used in this study.

The slag cement conformed to ASTM C989 (ASTM, 2018). Table 2 shows the mix proportions used in this study. The slag replacement for 28 MPa is 50%. The slag replacement for 38 MPa is 70%. The slag replacement for 44 MPa is 70%.

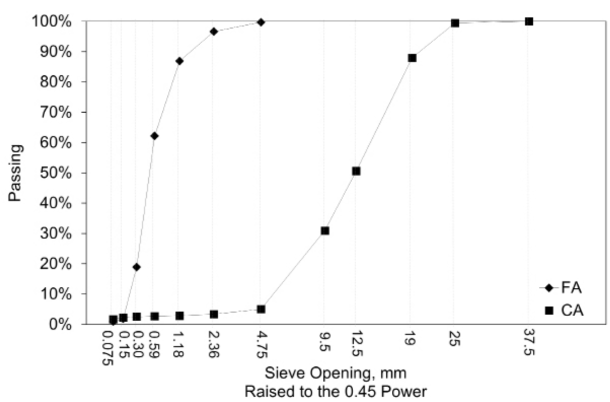

Figure 3: Gradation of aggregates.
Source: Author.

4. METHODS AND DISCUSSION

4.1. Data collection

Concrete from several construction sites for threshold buildings throughout Florida was sampled per ASTM C172 (ASTM, 2017) between May and September 2018 (Figure 4).

Property	*FA*	*CA*
Materials < 75 µm (%)	0,2	1,5
Fineness Modulus	2,34	–
SSD Specific Gravity (g/cm³)	2,69	2,42
Absorption (%)	0,3	3,9
Nominal Maximum Size (mm)	–	19

Table 1: Physical properties of aggregates.
Source: Author.

Notes: *SSD* is the Saturated-Surface Dry condition of aggregates; *FA* is the fine aggregate; CA is the coarse aggregate.

f'c	*CC*	*w/cm*	*CA*	*FA*
28 MPa	300	0,56	980	690
38 MPa	395	0,41	980	700
44 MPa	450	0,37	980	640

Table 2: Concrete mixtures.
Source: Author.

Notes: CC is the cementitious content; Cement is the Type IL-10 or PLC; Slag is the slag cement grade 120; CA is the coarse aggregate; FA is the fine aggregate; w/cm is the water to cementitious content ratio; quantities in kg/m^3.

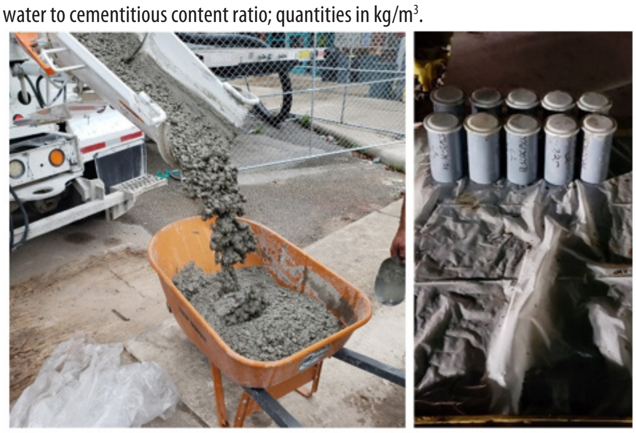

Figure 4: Sampling and temporary undisturbed storage of concrete specimens.
Source: Author.

A total of 958 concrete cylinders of 100 by 200 mm were molded and cured per ASTM C31 (ASTM, 2019b). The specimens were tested for σ at 7 and 28 days following the C39 (ASTM, 2020c). Figure 5 shows the σ results for the three concrete mixtures studied. Three specimens were prepared for testing at 7 days and three at 28 days for every 40 m^3 of concrete delivered in most job sites, while some only cast specimens for 28 days for contractual reasons. Two specimens were discarded due to damage during transport to the laboratory. A total of 345 specimens were tested for σ at 7 days and 613 at 28 days. The total of 205 sets of specimens for 28 days governed the sample representativity because the concrete strength must be achieved at such an age. The sets investigated represented 8200 m^3 of placed concrete. The f'_c of the three mixtures was exceeded within 7 days, which is a tendency in today's construction. Contractors can reduce construction time by removing forms earlier so that the following elements can be built, and the buildings can be delivered quickly.

The σ test results from different batch plants can vary. According to ACI 214R (ACI, 2019b), such variations typically originate from two sets of conditions: 1) Batch-tobatch due to ingredients or proportions of ingredients, mixing, transporting, placing, sampling, consolidating, and curing; and 2) Within-batch due to differences in sampling, specimen preparation, curing, and testing procedures.

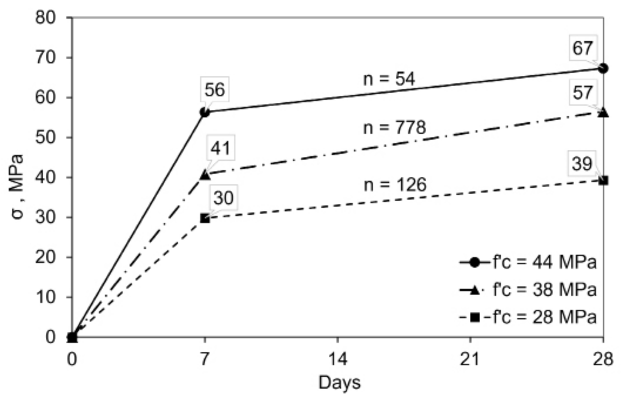

Figure 5: Compressive strength development of field specimens.
Source: Author.

The primary source of σ variation in this study should be attributed to the batch-to-batch, hence overall variation, because of the different ready-mixed concrete plants that produced the concrete. The data were statistically evaluated based on *S,* the criterion in ACI214R to classify the quality control of concrete production per concrete strength. For general construction and f'_c less than 35 MPa, the batch-to-batch control is considered excellent when S is below 2,8 MPa, very good when S is between 2,8 and 3,4 MPa, good for S between 3,4 and 4,1 MPa, fair for *S* between 4,1 and 4,8 MPa, or poor for *S* above 4,8 MPa. For general construction and f'_c greater or equal to 35 MPa, the batch-to-batch control is considered excellent when *S* is below 7 MPa, very good when S is between 7 and 9 MPa, good for S between 9 and 11 MPa, fair for S between 11 and 14 MPa, or poor for S above 14 MPa. At 28 days, two cylinders presented σ lower than the f'_c of 41 MPa, representing 0,4%. None of the cylinders for 28 and 44 MPa tested below the f'_c. Table 3 shows that the data analyzed in this study were classified between good and excellent, which indicates that the entire operational chain, including ingredients, mixing, transporting, placing, sampling, consolidating, and curing, was developed according to the standard procedures. The complete σ data set can be found in Tables A1 to A3.

f'_c	$S_{7\ days}$	Control	$S_{28\ days}$	Control
28	3,1	(Very good)	3,8	(Good)
38	9,5	(Good)	5,2	(Excellent)
44	11,0	(Good)	5,0	(Excellent)

Table 3: Batch-to-batch control classification.
Source: Author.

Notes: Classification of batch control per ACI 214R-11 Tables 4.3 and 4.4, based on the standard deviation (S) of general construction testing; quantities in MPa.

4.2. Required cementitious content

The test results presented in the previous sections were used to determine the required cementitious content (*RCC*) for each concrete mixture, as shown in Table 4. The f'_{cr} were calculated using equation 1 based on the actual *S* for each mixture using the z of 2,33 per the ACI standards. The difference between the σ reached by each concrete mixture and the f'_{cr}, the additional overdesign (*AOD*), was calculated and multiplied by the cementitious content ratios (*CCR*) to obtain the additional cementitious used in the mixtures. The *CCR* was calculated by dividing the cementitious content (*CC*) of the mixtures by the σ achieved. The required cementitious content (*RCC)* is the difference between the *CC* and the additional cementitious. The mixture f'_c = 28 MPa used 300 kg/m³ of cementitious, and its RCC was 282 kg/m³. The mixture f'_c = 38 MPa used 395 kg/m³ of cementitious, and its RCC was 350 kg/m³. The mixture f'_c = 44 MPa used 450 kg/m³ of cementitious, and its *RCC* was 372 kg/m³. The *RCC* calculated are aligned with the recently developed research. The cementitious content in concrete can be reduced by 25% without compromising the compressive strength and consistency. Such reductions can be achieved by optimizing binary and ternary aggregate systems (ANTUNES, 2018; ANTUNES and TIA, 2018a; ANTUNES and TIA, 2018c; CHUNG AND TIA, 2021; CHUNG et al., 2020).

f'_c, MPa	f'_{cr}, MPa	σ, MPa	*AOD*, MPa	*CCR*, kg/m³/MPa	*RCC*, %
28	36,9	39,3	2,4	7,6	282
38	50,1	56,5	6,4	7,0	350
44	55,7	67,3	11,6	6,7	372

Table 4: Required cementitious content in concrete.
Source: Author.

Notes: f'_c is the specified compressive strength at 28 days; f'_{cr} is the required compressive strength at 28 days; σ is the compressive strength at 28 days; *AOD* is the additional overdesign; *CCR* is the cementitious content ratio; *RCC* is the required cementitious content.

Figure 6 demonstrates the difference in cementitious content needed to produce concrete with a target strength. The *RCC* curve presented is particular for the materials used in this study and should be used as a reference for trail batches. It is recommended to obtain such curves for local materials by testing at least 30 specimens for statistical analysis.

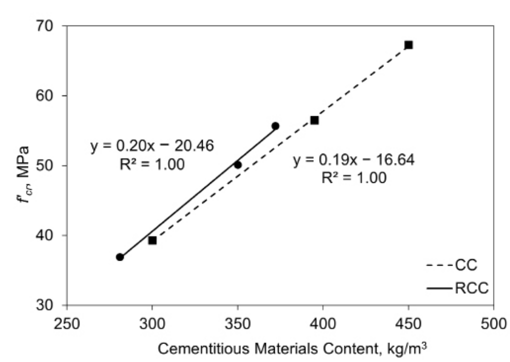

Figure 6: Cementitious content and required compressive strength.
Source: Author.

5. CONCLUSIONS

This experimental study aimed to identify the required cementitious materials content (*RCC*) to meet the overdesign (*OD*) based on 958 compressive strength tests (σ) representing 8200 m^3 of ready-mixed concrete for threshold buildings.

The following conclusions can be drawn from the results regarding the tested concrete:

• The actual *OD* in the concrete mixtures was 7 to 21% higher than required.

• The cementitious materials content should be reduced between 6 and 17% so that concrete can reach the required compressive strength (f'_{cr}) without cement overconsumption.

• The additional overdesign (*AOD*) increased significantly as the f'_c increased, indicating that concrete producers can be more cautious when the concrete reaches higher compressive strength (σ). That can be explained by the increase in batching errors as the amounts of materials increase.

Further research is needed to expand the range of cementitious contents and applications.

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Note: The complete data set comprised of 958 compressive strength (σ) tests is provided on our website for consultation.

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