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An Overview of the Application of Performance Based Specifications in Concrete Construction Projects

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Construction projects use prescriptive codes to regulate multiple stages of concrete construction activities. Prescriptive codes are suitable for design-bid-build projects as it provides sufficient details for different project parties. Despite of its advantage, prescriptive codes represent an impediment to the potential improvement of concrete mix characteristics, including immediate mix properties, long-term performance, and concrete sustainability due to the restrictions imposed on material selection, constituent proportions and batching and mixing procedures. To improve construction projects quality and long-term performance, current federal legislatures focus on the replacement of prescriptive codes with performance-based specifications, where the concrete mix is designed and optimized to attain specific long-term performance criteria decided according to the project service conditions. This research paper presents the possible outcomes of utilizing performance-based specifications in replacement of prescriptive codes in concrete construction; and presents the changes to be adopted in project quality control procedures to ensure its successful implementation in future projects. The results of this research show that performance-based specifications are advantageous in fast-track projects, including design-build project delivery. Concrete mixes produced according to performance-specs have superior long-term performance characteristics, higher durability, and improved sustainability. Due to the increased durability, structural concrete designed and poured using performance specs need lower maintenance intervention, which reduce construction projects life cycle cost.

Keywords: Prescriptive codes, Performance-based specs, Long-term performance, Durability, Life cycle cost.

Introduction

The construction industry comprises approximately 9% of the national gross domestic product (GDP) of the United States. Approximately 1.8 trillion dollars per calendar year is spent in construction projects including residential, commercial, heavy, and industrial projects in the local market (Akhnoukh, 2020). The construction industry utilizes different codes and specifications to control different construction activities; and provide guidelines to regulate the relation between different stakeholders of the construction project including the project owner, architect, project consultant, general and sub-contractors, and the construction manager. Different types of codes and specifications are available to provide different trades with design aids and charts to design different components of the construction projects, provide material specifications, regulations for the construction procedures, and site safety. Codes and specifications provides minimum provisions to ensure the safety and serviceability of the construction project .

In today's construction market, concrete is used in almost all stages of construction including the construction of different types of foundation, and in multiple stages of the super structure including the construction of columns, beams, girders, and slabs. Due to its market share, concrete is considered the dominant construction material. Several codes and specifications are used by design engineers, consultants, contractors, and construction managers to regulate their concrete construction activities, including American Concrete Institute (ACI) Codes, American Society of State Highways and Transportation Officials (AASHTO) Specifications, Precast/Prestressed Concrete Institute (PCI).

Specifications, and American Society for Testing and Materials (ASTM). The afore-mentioned codes and specifications are classified as prescriptive codes. Prescriptive codes are legal documents that prescribes a rigid description for the design and construction of the projects. In plain, reinforced, and prestressed concrete construction projects, a prescriptive code provides a specific concrete mix design including the proportions of mix constituents, minimum and maximum water-to-cement ratio, approved ranges for sieve analysis results of fine and coarse aggregates, and a detailed mixing and curing procedures. Prescriptive codes supply different project stakeholders with a set of fresh and hardened concrete testing to evaluate the produced concrete as slump testing for fresh concrete (ASTM C143, 2015), and compressive strength testing for hardened concrete (ASTM C39, 2018).

The compliance of project stakeholders and construction parties (design engineer, project manager, and contractors) with prescriptive codes provisions results in a successful completion of the construction project. The rigid provisions provided by prescriptive codes minimize potential conflicts during different activities execution. Despite these advantages, prescriptive codes provide a limitation to the ability of different parties within the project to use innovative approaches in executing their work. In addition, prescriptive codes predate new construction concepts including LEAN construction, construction sustainability, and ultra-high-performance materials. To-date revised prescriptive codes do not include performance-based provisions for concrete design. Thus, prescriptive codes don't provide sufficient flexibility in utilizing these new construction concepts, which adversely affects the project long term performance, life cycle cost, and sustainability.

History of Design Codes in Construction Industry

In modern history, building codes evolved with more provisions and specifications. The increase in code details is attributed to the nature of stakeholders participating in codes development including: 1) insurance industry: and its main purpose of providing standards to eliminate accidents, 2) local government: that target the development of regulations to deliver safe and economic projects for the welfare of its citizens and taxpayers, and 3) social organizations: which target the minimization of project impacts on the environment. The modern building code's main objective is to provide minimum provisions to ensure the structural integrity and proper use of construction materials without violating the predefined project budget and schedule.

To avoid construction conflicts and possible legal issues, modern codes provides strict provisions to follow during the project design (design codes) and during different projects construction phases (construction codes). Design and construction codes have built-in factors of safety to avoid potential failures under unforeseen events including extreme loading conditions, possible human errors in design and construction, and finally to account for potential flawed construction materials. The strict provisions and clauses qualified current design and construction codes to the term "prescriptive codes."

Literature Review

The perspective approaches are perceived as old and reliable methods of design in general, and for concrete mix design in specific. However, prescriptive codes and specifications are considered conservative, and may result in the consumption of larger amount of cement which negatively impacts the environment (Akhnoukh, 2018, Elia et al., 2019). Prescriptive codes and specifications for concrete mix designs focus on mix constituent selection, materials proportions, batching, mixing, pouring, compaction, and curing of concrete mixes. Concrete quality is primarily evaluated by measuring hardened concrete compressive strength. Recently, researchers have made significant progress in developing mixes with ultra-high compressive strength (Akhnoukh, 2021, 2020, 2019, 2013, and 2010). However, the ultra-high strength of developed mixes did not always translate to improved long-term performance (durability) (Shah et al., 2000). Recent research project showed that concrete problems such as alkali-silica reactivity and chloride ingress in concrete may result in expedited deterioration and premature failure to ultra-high strength concrete (Akhnoukh and Mallu, 2022, and Akhnoukh et al. 2014).). Currently, prescriptive codes assumes that concrete will be durable for its specific service life as long as it meets irrelevant prescriptive criteria as compressive strength (Beushausen and Luco, 2016). The lack of long-term performance evaluation of concrete represents a major deficiency in prescriptive codes (Beushausen et al., 2016). Unlike the prescriptive codes, performance specifications specify what is required from the concrete on short and long terms. Thus, the primary focus is on the concrete performance rather than on the concrete ingredients. Despite their major advantages, performance-based codes are not widely used in the construction market due to the lack of consensus for the term "Performance Specifications," as it can be interpreted differently (Bickley et al., 2006). Currently, several design codes are predominantly prescriptive. Yet, they have included few explicit guidelines to improve the long-term performance of concrete. Major prescriptive codes with performance-based added provisions are shown in Table 1. (Ali et al., 2021).

Table 1.
Performance specifications definitions according to different codes

Codes	Interpretation
CIB Working Commission W060	The practice of thinking and working in terms of end result and not the means
U.S. Federal Highway Administration	A performance specification define the performance characteristics of the end product and link them to construction
National Ready Mix Concrete Association (NRMCA)	A performance specification is a set of instructions that outlines the functional requirements for hardened concrete
Cement Association of New Zealand	A performance-based specification prescribes the required properties, but does not specify how they are developed.

Objectives and Methodology

The main objective of this research is to highlight the major differences between prescriptive and performance-based codes. This objective is attained by the implementation of the following methodology:

- Performance-based specifications in concrete construction is defined and interpreted
- Performance-based criteria for concrete design is selected and introduced
- Advantages of performance-based specifications are highlighted
- Challenges and limitations to the performance-based specification implementation in current construction market is investigated
- A case study is presented to highlight the major differences between prescriptive and performance-based specifications

Performance-Based Specifications in Concrete Construction

Concrete performance specifications avoid requirements for productivity methods including mixing, pouring, and compaction of concrete. In addition, the performance-based specifications do not limit the mix designer with traditional requirements for the selection of the mix constituents including a minimum or maximum cement content, a maximum content for supplementary cementitious materials (SCMs), a given range for the use of mixing water, and specific mixing time (Foliente, 2000). The move towards performance specifications for concrete projects requires a different quality control approach to assess the compliance of the concrete structures with the new specifications. Thus, traditional quality control techniques followed by prescriptive codes as compressive strength should no longer be used due to their limited ability to predict long-term performance of concrete.

The current attempts to produce performance-based specifications for concrete projects considers different set of tests to estimate the efficiency of the project and the potential performance under specific project criteria. Examples of concrete performance criteria and relevant testing techniques are:

1. Concrete resistivity to chlorides and sulfates: which improves the long-term performance of concrete structures due to the reduced rate of steel corrosion. To attain higher resistivity and lower rate of steel corrosion, concrete voids ratio should be minimized. Currently, researchers are considering electrical resistivity of concrete to assess the concrete voids ratio and their distribution, which can be related to the rate of steel corrosion in future concrete construction projects. The concrete surface electrical resistivity depends on measuring the electric current in Amps passing through the concrete when an electric current source of known potential is known. Surface resistivity testing, shown in Figure 1, is done according to AASHTO T358-17.

Figure 1: Wenner device for surface resistivity measurement

2. Concrete performance under freeze-thaw cycles: which is required in areas where temperatures fluctuate around freezing point. Increased resistivity of concrete requires even dispersion of micro-sized air voids among the concrete surface. Once free water within the concrete mix freezes and its volume increase, the micro-sized air voids can contain the expansion of frozen water particles without inducing internal pressure that cracks the hardened concrete. Current research is investigating the use of a super air meter in replacement to the regular air meter used in current concrete quality control measurements. The super air meter is used to calculate the size and dispersion of air voids within the concrete as compared to regular air meter which measure the overall voids content only.

3. Concrete maturity testing: which is used to estimate the cement hydration process based on the evolved heat as a result of water-cement hydration process. Maturity testing, shown in Figure 2, is done according to ASTM C 1074.

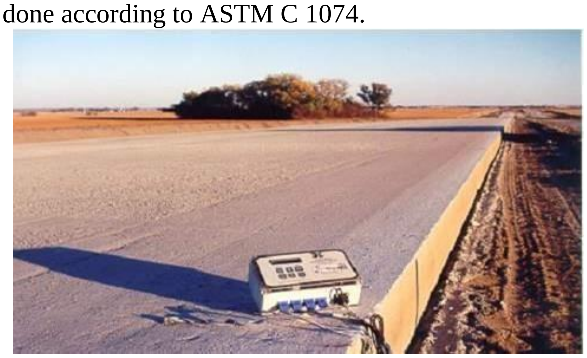

Figure 2: Maturity measurement of concrete (US DOT, 2000)

The afore-mentioned tests represents the main criteria in evaluating the performance of hardened concrete. Additional criteria could be used as shown in Table 2.

Table 2.

Test methods for performance-based specifications of concrete

Test	Description	Standard/Code
Volume of permeable voids	Test for volume of permeable voids	ASTM C642
Accelerated carbonation test	Evaluate carbonation resistance of concrete	ISO 1920 Part 12

Petrographic test	Examines and evaluates microstructures of concrete	ASTM C457
Linear polarization resistance	Measure corrosion rate on steel rebars	RILEM TC 154-EMC
Mass loss test	Determine mass loss due to moisture migration	ASTM C1792
Abrasion test	Assess abrasion resistance	ASTM C944/C779

The performance specifications of concrete require the establishment of a framework to regulate its use in current and future construction projects (Lobo et al., 2006). The established framework should establish standards for concrete production facilities, project requirements that list the expected performance of hardened concrete, a series of field acceptance tests that can assess long-term performance of concrete.

Advantages of performance-based specifications

Performance-based specifications are currently introduced to the construction market to attain specific targets and objectives. Despite their limited incorporation in construction project documentation in today's construction market, performance specifications will be increasingly used in future projects in the local market due to their positive impact on site constructions activities, and the improved future performance of the completed project. The following represents the possible advantages to be attained by the implementation of performance-based specifications in construction projects:

1. Increased flexibility in activities execution. This is attributed to the fact that the success completion of the construction activity will be judged based on specific performance criteria, and not according to rigid production techniques or prescribed instructions.
2. The performance-based specifications are dynamic. It can accept or adopt different project conditions. This flexibility results in a seamless workflow in projects with tight schedules and large number of critical activities.
3. Performance-based specification is mainly concerned with quality of the end product. Taking concrete construction as an example, the application of performance specs results in concrete with higher durability, long-term performance, and improved resistivity to adverse environmental conditions. This leads to project reduced maintenance and a lower life cycle cost.
4. Increased project sustainability is attained due to the reduced waste in construction material. In addition, performance-based specs allow the contractor to use innovative green and economic materials in construction as long as the final required performance is attained.
5. Performance-based specifications are suitable for new and advanced construction techniques as construction using 3-D printers and tilt up structures. In addition, these specifications are advantageous in construction of project with severe loading uncertainty as in blast resistant structures for army and homeland security projects, structures in regions with high seismic activity, and construction in hurricane and tornado affected regions.

Finally, performance-based specs, due to their flexibility, is suitable to new project delivery methods. In recent studies, project delivery methods as design build (DB), integrated project delivery (IPD), and construction management at risk (negotiated work) are increasingly considered in the local construction market. These projects will increasingly utilize performance-based specifications to enable flexible and seamless workflow using minimal hard and prescriptive language during the project activity execution.

Challenges and Limitations of Implementing Performance-Based Specifications

The main advantages of performance-based specifications are exploited when used in construction projects with specific parameters relevant to project nature, loading, and environmental conditions. Despite of their advantage, performance-based specifications are faced with multiple challenges that limits their use on a larger scale in construction projects. The main impediments to the incorporation of performance-based codes in construction projects are:

1. Performance-based specifications do not include rigid guidelines for material production. This might result in increased legal issues among different project stakeholders.
2. Lack of technical knowledge regarding the performance matrix to be used in the assessment of concrete performance.
3. Current material specifications provide adequate provisions to apply prescriptive codes. Additional research, specifications, and guidelines are required to enable project designers and contractors to adopt performance-based specs in their projects.
4. Performance-based specifications are not suitable for all project delivery methods. As an example, performance-based specs are not suitable for design-bid-build projects, where concise and specific and strict language is required.
5. A Lack of quality control testing procedures to be used when performance-based specs are adopted. For example, current quality control procedures for concrete uses slump test for fresh concrete and compressive strength testing for hardened concrete. Both tests are suitable for prescriptive codes. Additional research is required to develop different testing techniques to assess performance-based parameters.

Case Study

The application of prescriptive codes in developing green concrete mix designs will not provide the mix designer with the flexibility to eliminate or substantially reduce the portland cement content within the mix design. On the contrary, performance-based code provides the design engineer with flexibility in material selection, batching, mixing, pouring, finishing and curing. Table 3 compares the impact of different codes on the final sustainability of concrete mix.

Table 3

Comparison of prescriptive and performance-based codes impact on concrete sustainability

Specification Provision	Prescriptive Codes	Performance-Based Codes	Notes
Cement type & source	Restricted	Geopolymers are allowed	Using geopolymers eliminate cement and enhance concrete sustainability
Aggregate type & source	Restricted	Recycled concrete use allowed	The use of recycled building materials add LEED points
Supplementary cementitious materials (SCMs)	Maximum percentage specified	SCM could replace 100% of cement	Higher SCMs percent reduces cement content and increase durability
Mixing water	Potable water required	Possible use of alkaline activators, as in Geopolymers	Mandated use of water will not allow for producing geopolymer concrete with alkaline activators.

Discussions and Conclusions

Most of the current construction projects within the United States utilize prescriptive codes to control and judge different construction activities. Prescriptive codes provide general contractors with solid guidelines in performing their jobs and in the assessment of the quality of the contractor outcomes. Despite their advantages, these codes confine the contractor's ability in using new technology, new materials, and/or hinders the contractor capabilities in selecting novel approaches in job sites.

Current research is providing the construction market with different reasons to transform the project codes and specifications into performance-based specifications. The major advantages of performance-based specifications include: 1) the flexibility provided to the project designer and contractor to select innovative approaches to design and execute different projects activities, 2) the dynamic nature of performance-based specifications, which allows the project designers and contractors to select their materials, construction methods, and quality control procedures according to the project specific limitations, and 3) performance-based codes and specifications are suitable to the increasingly-adopted design-build project delivery due to its flexible nature.

In this research, the use of performance-based specifications in concrete construction is investigated versus traditional prescriptive codes. The provisions, advantages, and disadvantages of both types in concrete construction activities were investigated including the possible standard testing used to assess the quality of the produced concrete when the two different codes are used. The research findings showed that prescriptive codes could be advantageous in design-bid-build projects where rigid documentation are required, mix constituents should be predetermined for project pricing purposes, and mixing and curing procedures are to be prespecified for the contractor. On the other hand, performance-based specifications advantages were significant when non-traditional projects are considered, including projects affected by large non-conventional loads and stresses resulting from freeze-thaw cycles, length changes due to thermal variations, or extreme environmental attacks from soil and water contamination at the project site.

The research outcomes recommend the implementation of performance-based specifications on a larger scale within the construction market in the United States. Performance-based specification flexibility provides the project designer and contractor with the flexibility needed to improve the quality of the construction project; and improve its long-term performance. Improved project quality results in lower demand for maintenance and repair activity, which reduce the life cycle cost of construction projects.

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