Report on Behavior of Fresh Concrete During Vibration

Reported by ACI Committee 309

Bradley K. Violetta
Chair

Timothy P. Dolen*	Glenn A. Heimbruch*	Patrick F. O'Brien, Jr.	H. Celik Ozyildirim
Chiara F. Ferraris*	Gary R. Mass	Larry D. Olson	Steven A. Ragan
Jerome H. Ford	Richard E. Miller		

*Subcommittee members who prepared this report.

This report covers the rheological and mechanical processes that take place during consolidation of fresh concrete. The first chapter presents the historical developments relative to consolidating concrete. The second chapter provides notations and definitions. The third chapter deals with the rheological behavior of concrete during consolidation and the associated mechanisms of dynamic compaction. The fourth chapter presents the principles of vibratory motion occurring during vibration, vibratory methods, and experimental test results. Continuing research in the field of concrete vibration, as evidenced by the extensive literature devoted to the subject, is addressed.

Keywords: admixtures; aggregates; aggregate shape and texture; aggregate size; amplitude; compacting; consolidation; damping; energy; fresh concrete; hardening; history; mechanical impedance; mixture proportioning; reviews; rheological properties; stability; vibrations; vibrators (machinery).

CONTENTS

ACI 309.1R-08 supersedes ACI 309.1R-93 and was adopted and published August 2008.

CHAPTER 1—INTRODUCTION AND SCOPE

At the turn of the twentieth century, concrete was generally placed as very dry mixtures, and was deposited in thin lifts and rammed into place by heavy tampers, which involved extensive manual labor. Typical structures, such as foundations, retaining walls, and dams, contained little or no reinforcement. The concept of rammed concrete in thin lifts can be traced back to the early Roman times, when the Pantheon was built. Many of these structures are still in service, proving that this type of construction produced strong, durable concrete.

In the early twentieth century, the common use of reinforcing steel in concrete changed the consolidation requirements for concrete. Concrete sections were greatly reduced in thickness. Constructors found that the dry mixtures could not be tamped in the narrow forms filled with reinforcing steel and, consequently, water was added to facilitate placement into forms without regard to effects on the mixture itself. The change from massive tamped concrete structures in the early 1900s to relatively thin, reinforced concrete structures was a major advance in engineering practice, but did not necessarily result in immediate improvements in concrete quality. The dry, tamped concrete structures were somewhat less permeable than the wet concrete placed into the first reinforced structures. Methods other than tamping were tried to consolidate stiffer concrete. Compressed air was introduced into the fresh concrete through long jets. The practice of chuting concrete into place resulted in excessively wet mixtures as the water content was increased (without increasing the cement) to allow the mixture to flow in chutes (Walter 1929). It became apparent that these wet mixtures did not produce good concrete (Engineering News Record 1923). The result was lower strength, durability failures, and increased drying shrinkage and cracking. The poor durability of these first reinforced concrete structures was of great concern to early practitioners. These mixtures would be described as "wetter," though the slump test was yet to be standardized.

The water-cement ratio concept, postulated by Abrams around 1920, demonstrated that the quality of concrete dropped rapidly as more water was added to the mixture (Abrams 1922a). In addition, the development of the traditional slump test around 1922 gave the first measurable parameter for indicating concrete consistency suitable for placement and an indication of quality (Abrams 1922b). Abrams documented an increase in compressive strength by compacting low-consistency concrete with mechanical jigging.

Difficulty consolidating concrete in reinforced and mass concrete structures continued to be a problem until the introduction of internal concrete vibrators in the early 1930s (McCarty 1933). The use of vibrators allowed stiffer mixtures with less water to be placed, increasing both concrete strength and durability and decreasing shrinkage. In mass concrete dams, the introduction of the vibrator allowed the placement of very stiff concrete in thick lifts with lower water contents and subsequently less cement, which reduced thermal cracking in dams. Consolidation by internal vibration increased the rate of placement per day, and reduced internal flaws, such as cold joints.

ACI Committee 609 (1936) described the benefits of vibrators but was not able to explain the interaction between a vibrator and fresh concrete. The frequencies of the early 1900s vibrators were limited to 3000 to 5000 vibrations per minute (50 to 80 Hz) because of design and maintenance problems. When it became apparent that higher frequencies were possible and more effective in consolidating concrete, vibrator manufacturers made the necessary improvements.

The following is an historical listing of notable research on the consolidation of fresh concrete. Observations were made on the effect of air entrainment introduced in the late 1940s on concrete consolidation. Air entrainment makes the mixture more cohesive, and enhances particularly lean mixtures deficient in fines, as well as mass concrete.

L'Hermite and Tournon (1948) reported fundamental research on the mechanism of consolidation. They found that friction between the individual particles is the most important factor in preventing consolidation (densification), but friction is practically eliminated when concrete is in a state of vibration.

Meissner (1953) summarized research and reviewed state-of-the-art equipment and its characteristics.

ACI Committee 609 (1960) stated recommendations for vibrator characteristics applicable to different types of construction and described field practices.

Walz (1960) described the various types of vibrators—internal, surface, form, and table—and their application. It was shown that the reduction in internal friction is primarily the result of acceleration produced during vibration.

Rebut (1962) discussed the theory of vibration, including the forces involved, the types of vibrators and their application to different classes of construction, and vibration-measuring devices.

Ersoy (1962) published the results of extensive laboratory investigations on the consolidation effect of internal vibrators. Ersoy varied the concrete consistency, size and shape of form, and vibration parameters and concluded that the eccentric moment, defined as the mass of the eccentric times its eccentricity (distance between the center of gravity and the center of motion), and frequency are important factors for determining the consolidation effectiveness of an internal vibrator.

Kolek (1963) described vibration theories, formulas, and experimental work aimed at a better understanding of the processes involved. He determined that consolidation occurred in two stages: the first stage comprised the major subsidence or slumping of the concrete, and the second stage involved deaeration (removal of entrapped air).

Kirkham (1963) developed empirical formulas to explain the compaction of concrete slabs by the use of vibrating beams or screeds on the surface. The force, amplitude of vibration, and the vibration frequency were found to be the most important factors affecting the degree of consolidation.

Murphy (1964) published a summary of post-World War II British research, and compared the findings and claims of the different investigators. The studies made by Cusens (1955, 1956), Kirkham (1963), and Kolek (1963) on the subject of consolidation were particularly noteworthy.

Forssblad (1965a) reported on measurements of the radius of action of internal vibrators operating at different frequencies