CHAPTER 1
INTRODUCTION

1.1 FIELD OF STUDY

Concrete, one of man-made materials, represents the most widely used construction material. Concrete composes of sand, coarse aggregate (such as gravel, dolomite, or limestone), Portland cement, and water. However modern concrete often contains mineral components that have very specific characteristics that give specific properties to concrete (Aïtcin, 2000). The ratio of these materials dictates the strength and performance of the concrete. Worldwide, there has been outstanding growth in the Portland cement concrete industry in the 20th century as concrete has become the material of choice for construction of bridges, dams, highways, and urban transit facilities. Due to increasing urbanization, the consumption of concrete is expected to grow steadily during this century as well (Mehta, 1997).

In the 1930s, when the current boom in concrete construction began, it was generally believed that concrete structures typically designed for a service life of 40 to 50 years would actually last much longer with little or no maintenance. But after the publication of a report by the National Material Advisory Board (National Material of Science Report, 1987), the situation was changed and durability of concrete started to attract the attention of many engineers and researchers in the United States. According to this report, approximately 253,000 concrete bridge decks, some of them less than 20 years old, were in varying states of deterioration and about 35,000 were being added to this list every year (Mehta, 1997).

In the same year, Litvan and Bickley (1987) published the results for a survey on the durability of concrete in automobile parking structures in Canada. Numerous parking structures had shown serious deteriorations before the end of their intended service life. Recently, cases of premature distress of concrete were also reported in several countries (Shayan and Quick, 1992; Mehta, 1997). So, any concrete, if we look far enough into the future, will end its service life as limestone, clay components, and silica sand, which are the most stable mineral forms of calcium, silica, iron, and aluminum in the earth's environment. Therefore, all we can do as engineers is to extend the service life of this artificial rock as much as possible (Aïtcin, 2003).

Among the several durability-related problems of concrete, alkali-aggregate reaction (AAR), since it was first identified in the early 1940s by Stanton, became a major durability problem in many parts of the world. AAR is a reaction in mortar or concrete between reactive mineral phases in the aggregate and alkali hydroxide in the pore solution of concrete. Sources of such alkalis include internal sources like the alkali from Portland cement and external sources such as de-icer salts. This reaction can lead to premature distress and deterioration of concrete structures affected (Milanesi et al., 1996; Fournier and Bérubé, 2000; RILEM AAR-1, 2003). There are two types of AAR, namely, alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). Although both reactions have different mineral phases and reaction mechanisms, they both lead to expansion and cracking of concrete.

ACR was first reported in the late 1950s by Swenson in Ontario, Canada (Swenson, 1957). Typically, argillaceous dolomitic limestones susceptible to ACR petrographically consist of rhombic crystals of dolomite, 20 to 50 µm in size, disseminated in a matrix of microcrystalline calcite (typically 2 to 6 µm) and clay minerals (<2 µm in size) (Swenson and Gillott, 1960; Fournier and Bérubé, 2000). On the other side, ASR is fundamentally related to the increased solubility/instability of amorphous, disordered, poorly, micro- or cryptocrystalline forms of silica in high pH solutions. The rocks susceptible to ASR, according to the silica form, are either poorly crystalline silica minerals (such as Opal, Tridymite, Cristobalite) or quartz-bearing rocks incorporating very fine-grained quartz (micro- to cryptocrystalline) (Diamond, 1976; Fournier and Bérubé, 2000). AAR may not be the main cause of concrete deterioration in many concrete structures but it may promote other forms of deteriorations such as freezing-thawing, sulphate attack, and reinforcement corrosion through opening the required pathways for aggressive substances to enter concrete and result in many durability problems. In addition, ASR can affect the operation of certain types of structures where the expansion may result in the misalignment or distortion of concrete elements supporting mechanical equipment such as sluice gates or turbines (Cavalcanti et al., 2000; Gaudreault, 2000; Gocevski and Pietruuszczak, 2000).

Evaluating the alkali-reactivity of aggregates using various analytical and mechanical test methods was the focus of concrete researchers for many years. Various recent studies are being conducted aiming to develop the appropriate quick and reliable test method for alkali-reactivity of aggregates. Petrographic analysis, however, should usually be the first step in evaluating the alkali-reactivity of aggregate; some reactive constituents were found mixed within the aggregate matrix and were not always detectable in petrographic analysis (RILEM AAR-1, 2003). Such aggregates showed expansion cracks after many years. Consequently, other tests, either accelerated or long-term tests, should be employed in evaluating the alkali-reactivity of aggregate in addition to the supplementary analytical techniques such as X-Ray Florescence (XRF), X-Ray Diffraction analysis (XRD), and Scanning Electron Microscopy (SEM) that are being used successfully.

Most of current specifications assess the alkali-reactivity of aggregate knowing that it is un-satisfactory to evaluate the alkali reactivity of aggregate based on only one test. It is also known that no single test will be entirely valid with all types of aggregates. Moreover, some of the test methods may be misleading particularly when dealing with marginally-reactive aggregates (Grattan-Bellew, 1997; Grattan-Bellew et al., 2003). However, the mechanical test methods such as accelerated mortar bar test (AMBT) and concrete prism test (CPT) still represent the practical solutions for construction industry.

The Concrete Prism Test (CPT) is recognized as the most reliable laboratory test and has been used for evaluation of alkali-silica and alkali-carbonate reactivity of aggregates. However, the relatively long test duration (one year for assessing aggregate reactivity and 2 years for evaluating the efficacy of preventive measures) put the test to be used, most of the times, as a reference test for assessing the reliability of accelerated tests rather than being used as a quality control test (Grattan-Bellew, 1997; Lu et al., 2008b). Moreover, the test was found to be severe for many aggregates from Quebec (Canada), where the aggregates produced expansion more than 0.04 % after one year, while just a few of them were found deleteriously reactive in existing structures (Bérubé et al., 2000; Fournier and Bérubé, 2000). In contrast, other researchers found that the expansion of field concrete is higher than that produced in CPT due to alkali leaching in the moist environment during the test (Rogers and Hotoon, 1991; Rivard et al., 2007).

As a matter of fact, accelerated tests such as AMBT are considered the conservative choice and meet the practical engineering needs, although the use of these accelerated tests does not always solve all the problems associated with the evaluation and acceptance of aggregates for use in concrete. The severity of the test procedures, which includes the use of relatively small aggregate sizes, high temperature, and high alkali regimes, makes some aggregates fail the test despite their satisfactory performance in field concrete. In contrast, AMBT could not identify the alkali-reactivity of some carbonate aggregates containing dolomitic limestone (Fournier and Bérubé, 2000; Lu et al., 2006a; Lu et al., 2008b). Accordingly, such accelerated tests may be used to accept an aggregate but not to reject it (Grattan-Bellew, 1997). So, it looks satisfactory to employ a combination of tests to determine if an aggregate will be accepted for a particular job mix or not, with attention for the aggregates without prior field performance records.

On the other side, for new sources of carbonate aggregates, rock cylinder test represents the most reliable test intended for evaluating alkali-carbonate reactivity. Moreover, concrete microbar test (CMBT) was adopted by RILEM AAR-5 as a standard test method for alkali-carbonate reactivity of aggregates. Recently, the test was also proposed as a universal test method for both alkali-silica and alkali-carbonate reactivity of aggregate (Grattan-Bellew et al., 2003; Lu et al., 2008b). So, adopting these two test methods for alkali-reactivity of Egyptian aggregates, which are basically carbonate rocks, warrants investigation.

The severe impact of AAR-induced expansion on the various engineering properties of concrete may lead to premature deterioration, requiring costly repair and rehabilitation of concrete structures to maintain their intended function. So, precautions must be taken to avoid excessive expansion due to AAR in concrete constructions. Although, extensive knowledge is available regarding the reaction mechanism, the aggregate reactive constituents that may lead to deleterious expansion, and the adequate precautions that can be taken to avoid the resulting stress, our knowledge about ASR and ACR is still not sufficient particularly with respect to the methods used to repair the affected concrete, and means to control the subsequent expansion in existing structures (ACI 221.1R, 1998). Evaluating the alkali-reactivity of Egyptian aggregate is still in the preliminary stages, and there is no record of aggregate reactivity in Egypt. Therefore, it is imperative to study the reactivity of aggregates from different sources in Egypt and the impact of AAR-induced expansion on engineering properties of concrete, such as strength and permeability.

Although using non-reactive aggregate is considered the best mitigation measure against AAR (Bèrubè et al., 2000; Bragg, 2000; Fournier and Bèrubè, 2000; Rogers et al., 2000), this is not often possible or economical especially when the non-reactive aggregate sources are far from the construction site. In such cases, other mitigating measures are required. Low-alkali cement (LAC), if available, is usually effective in reducing expansions due to ASR (Fournier and Bèrubè, 2000; Bragg, 2000; Rogers et al., 2000). However, the use of LAC was found inefficient in controlling expansion due to ACR (Swenson and Gillott, 1964; Rogers and Hooton, 1992; Shehata et al., 2009). Stanton's work in 1940 demonstrated that the deleterious reaction due to ASR could be prevented by incorporating LAC which was defined as the cement with $Na_2O_{eq}<$ 0.6 %, or by pozzolans in the mixture (Buck et al., 1953; Fournier and Bèrubè, 2000).

Adequate selection of supplementary cementing materials (SCMs) such as silica fume, fly ash, and slag can also be used to minimize or sometimes prevent excessive expansions produced by ASR (Swamy and Al-Asali, 1990; Fournier and Bèrubè, 2000; Rogers et al., 2000). There are many factors that affect the efficiency of SCMs in preventing the damaging reaction due to ASR such as the quantity of SCMs, its chemical composition, the nature and level of reactivity of aggregate and the alkali content provided by the Portland cement. Shehata and Thomas (2000) found that the amount of fly ash necessary to prevent ASR-expansion depends on the chemistry of fly ash where the most effective mitigation was obtained by using low-calcium fly ashes. On the other side, there is a general agreement between researchers that there is no preventive measure for the deleterious expansion due to ACR (Swenson and Gillott, 1960, 1964; Rogers et al., 2000, Shehata et al, 2009, Gifford and Gillott, 1996). Furthermore, slag has been found effective in reducing ASR-induced expansion even though it apparently increases expansion due to ACR compared with high-alkali cement (Rogers and Hooton, 1992; Thomas and Innis, 1998).

Carbonate rocks susceptible to alkali-reactivity are either expanding rocks or rim-developing rocks. The expanding rocks show rapid expansion in concrete and in highly alkaline solutions. Such rocks can be characterized based on the compositional and textural features. While, rim-developing rocks are always accompanied by dedolomitization but the rim formation has no correlation with their deleterious expansion (Katayama, 1992). Unlike ASR, the reaction mechanism of alkali-reactive carbonate rocks is not fully understood and extensive research has been recently conducted to explain the causes of deleterious expansion. Moreover, previous research suggested that rocks from different parts of the world show different reaction features. So, it is important to study the reaction mechanism of Egyptian carbonate aggregates as such aggregate sources may show different reaction mechanism.

1.2 PURPOSE OF THE STUDY

The common siliceous (such as gravel) aggregate sources that were being used in Egypt in the last two decades are in severe shortage and unavailable in many parts of Egypt. There is an increasing concern regarding the alkali-reactivity of Egyptian carbonate rocks including the dolomite and limestone aggregates that are being used extensively in the construction industry and represent promising aggregate sources. One of the main causes is that these aggregates may undergo ACR especially that ACR occurs even with LAC ($Na_2O_e \geq 0.4$ %) which is usually used in Egypt. However there are no documented cases of structures that suffer AAR in Egypt, the reaction may be present in some structures but is wrongly classified as another form of concrete deterioration such as sulphate attack or reinforcement corrosion. The proper evaluation for the alkali-reactivity of various Egyptian aggregate sources is therefore essential.

The widely used aggregates in Egypt now are carbonate rocks. While CPT was proposed by CSA A23.2-14A for testing alkali-silica and alkali-carbonate reactive aggregates, the one year test period of the test limits its use in quality control purposes. The rock cylinder test, as per ASTM C 586, represents an adequate test for alkali-carbonate reactive aggregates particularly with new aggregate sources. Quick evaluation can be conducted within 4 weeks as well. Because the sample preparation for this test is relatively impractical, a practical and economical method for sample preparation is therefore required.

Concrete Microbar Test (CMBT) proposed by many researchers as a universal test for both alkali-silica and alkali-carbonate reactive aggregates, is a promising test as its duration is relatively short. In order to adopt this test as a standard test for the alkali-reactivity of Egyptian aggregates, the effect of aggregates size, test duration, alkali ions type, should be investigated. It is recommended to employ more than one test for evaluating the alkali-reactivity of the aggregates as misleading results are usually obtained with marginally reactive aggregates (Grattan-Bellew, 1997; Grattan-Bellew et al., 2003; Lu et al., 2008b).

Since ASR and ACR were first reported by Stanton in 1940 and Swenson in 1957, most of the research has been directed to understand the reactions mechanisms, suggesting the proper mitigating measures needed to reduce the expansion. Some studies have been carried out to study the effect of ASR on the various engineering properties of concrete, but very limited data are available on the effect of ACR on the various properties of concrete incorporating marginally or highly-carbonate reactive aggregates. Although the alkali-carbonate reactive aggregates are not allowed to be used in concrete, aggregates that marginally meet the expansion criterion are, however, very common and are allowed for use as concrete aggregates in many parts of the world. The impact of ACR-induced expansions on the various engineering properties (such as strength and permeability) of concrete incorporating either marginally-reactive or highly-reactive carbonate aggregates should therefore be investigated. Furthermore, the use of either mineral admixtures such as fly ash (FA), silica fume (SF), metakaolin (MK), and slag or LAC, as mitigation measures to suppress expansion of marginally-carbonate reactive aggregates, should also be studied.

The mechanism of ACR-induced expansion was studied by many researchers. Some attributed the expansion to dedolomitization reactions and that clay minerals, scattered within the matrix of alkali-carbonate reactive rocks, open the pathways for alkalis to reach dolomite grains (Deng and Tang, 1993; Liang and Tang, 1995). Others claimed that the expansion is due to swelling of clay minerals and that the dedolomitization reaction facilitates the water entry to the un-wetted clay minerals (Swenson and Gillott, 1960, 1967). A third opinion is that the expansion can be attributed to ASR of some crypto-crystalline components and clay minerals scattered in carbonate rocks (Katayama, 2004; Katayama and Sommer, 2008). There is a recent tendency to accept ACR as just another variant of ASR (Grattan-Bellew et al., 2008). Because of these contradictions in interpreting the expansion mechanism due to ACR, it is important to study the reaction mechanism of the relatively new Egyptian carbonate aggregates that have not been adequately tested.

In an effort to gain improved understanding of the above-mentioned aspects, the present study was undertaken with the following objectives:

1- To evaluate the alkali-reactivity of various sources of Egyptian aggregates representing wide range of mineralogical composition and petrographic characteristics. To compare these aggregates with well-known alkali-reactive Canadian aggregates: Spratt (ASR) from Ottawa and Pittsburg (ACR) from Kingston as well.
2- To employ the analytical test techniques such as petrographic examinations on thin sections, XRD, and SEM as supplementary tools for evaluating the potential alkali-reactivity of Egyptian aggregates, in addition to the standard test methods.
3- To evaluate the efficiency of Concrete Micro-Bar Test (CMBT) suggested by many researchers as an accelerated test for both alkali-silica and alkali-carbonate reactivity of Egyptian aggregates. The development of a practical and economic method for the sample preparation to run the rock cylinder test is to be proposed as well.
4- To study the impact of various levels of expansion due to ACR on the various engineering properties of concrete, such as strength and permeability.
5- To propose adequate mitigation measures such as mineral admixtures or LAC, to suppress the expansion due to AAR of the Egyptian aggregates. The efficiency of various SCMs such as silica fume (SF), fly ash (FA), slag, and metakaolin (MK) as well as ternary blends of SF/FA or SF/slag on ASR-induced expansion of representative Egyptian aggregates sources are also to be investigated.
6- To study the various factors affecting the expansion due to AAR of Egyptian carbonate aggregates such as the alkali level, temperature, and the clay minerals content. The mechanisms of AAR for representative Egyptian aggregate sources are also to be investigated.

1.3 OUTLINE OF THESIS

This thesis is divided into eight chapters, following this introduction (chapter 1), chapter two, represents a general review for the different types of AAR and the essential components required for the reactions to occur. Chapter 2 also provides a review on the different hypotheses that explain the reaction mechanisms for the various types of aggregates. Furthermore, the symptoms of AAR and its effects on the various engineering properties of concrete are summarized in this chapter. A summary for the test methods widely used for evaluating the alkali-reactivity of the aggregates is considered as well. Finally, the various preventive measures used to suppress the AAR-induced expansions are briefly reviewed.

Chapter 3 introduces the experimental work, materials used, mix proportions, specimens preparation and the testing techniques adopted throughout the present investigation.

Chapter 4 involves the evaluation of the alkali-reactivity for six representative sources of Egyptian aggregates having different composition and petrographic characteristics. In addition, three reference Canadian aggregates (Spratt, Pittsburg, and non-reactive) representing a wide range of alkali-reactivity were utilized for comparison. The petrographic examination on thin sections and the test results obtained from the different mechanical tests such as CPT, AMBT, CMBT, and rock prism test are presented in this chapter.

Chapter 5 deals with CMBT as a proposed test method for the alkali-reactivity of the Egyptian aggregates. The various variables that affect the test such as types of alkali ions, samples exposure conditions, temperature, and aggregate size are summarized. A practical and economical method for sample preparation of rock prism test is suggested.

Chapter 6 outlines the impact of the different levels of expansion due to ACR on the various engineering properties of concrete incorporating reactive, marginally-reactive, and non-reactive aggregates. The effect of various SCMs such as FA, SF, MK, slag, and ternary blends of SF/FA and SF/slag on reducing AAR-induced expansions are demonstrated in this chapter.

Chapter 7 involves the study of the various factors that affect the alkali-reactivity of Egyptian aggregates such as alkali levels and temperature. The effect of clay minerals on the expansion of the rocks susceptible to ACR is investigated. The interfacial zone between the aggregates and the surrounding cement paste are studied. Finally, the interpretation of the alkali-reactivity of the Egyptian aggregates is presented.

Chapter 8 provides the general summary, the conclusions of the work conducted throughout this study and recommendations for further studies.