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A comprehensive investigation into the effect of aging and coarse aggregate size and volume on mechanical properties of self-compacting concrete

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ABSTRACT

The popularity of self-compacting concrete (SCC), as an innovative construction materials in concrete industry, has increased all over the world in recent decades. SCC offers a safer construction process and durable concrete structure due to its typical fresh concrete behavior which is achieved by SCC's significantly different mixture composition. This modification of mix composition may have significant effect on the hardened mechanical properties of SCC as compared to normal vibrated concrete (NVC). Therefore, it is necessary to know whether the use of all rules and relations that have been formulated for NVC in current design codes based on years of experience are also valid for SCC. Furthermore, this study represents an extensive evaluation and comparison between mechanical properties of SCC using current international codes and prediction equations proposed by other researchers. Thus, in this experimental study, major mechanical properties of SCC are investigated for twelve SCC mixes with wide spectrum of different variables i.e. maximum coarse aggregate size, coarse aggregate volume and aging. In the present study, an extensive body of data reported by many researchers for SCC and NVC has been used to validate the obtained results.

1. Introduction

During the past four decades, self-compacting concrete (SCC) has been known to eliminate difficulties associated with the task of mechanical vibration and casting process including inadequate or excessive compaction. Use of SCC, due to its important properties, leads to construction of durable and reliable concrete structures [1,2]. SCC is considered as a flowable concrete which is able to spread and compact under its own weight, filling the molds with restricted areas and complex shapes in structural members including heavily reinforced members while no vibration is needed and no segregation or bleeding occurs [3,4]. Recently, SCC has gained wide attention across the world for different applications such as in bridges, tunnels and high-rise buildings [5]. SCC presents remarkable benefits such as better quality of concrete produced as well as a safer, faster and more economical concrete construction process [6]. Typically, in order to attain this behavior, compared to normal vibrated concrete (NVC), higher cement content and very powerful superplasticizers should be used in SCC which leads to increase of cost and temperature rise [7]. Thus, other ultra-fine particles such as fly ash, limestone powder or slag can generally be used as partial replacement of cement [8]. Many researchers reported that these modifications in the mix design may have significant effects on the rheological and mechanical behavior of SCC, as opposed to NVC, in hardened state [9,10]. Many researchers have reported that mechanical properties are significantly related to mix design parameters [11]. Since mechanical properties such as compressive strength, tensile strength and modulus of elasticity are three key properties that affect the safety, durability and serviceability of a concrete member, studies on the mechanical properties of SCC have been a top research topic in the recent years [12–14]. Compressive strength, as a key property governing other mechanical properties which is defined as

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the capacity of axial load bearing, is the most important index in classification of concrete in national and international codes. The importance of accurate prediction of compressive strength in SCC is due to the importance of precise prediction of ultimate capacity of concrete members in design process of structures. Exact determination of deformation of concrete members, calculation of the structure deflection under wind and earthquake loadings, calculation of elastic shortening and creep loss in pre-stressed concrete members specially in bridges depend on precise determination of modulus of elasticity. Furthermore, exact determination of minimum amount of reinforcement in concrete members in design process, assessment of crack width and fracture behavior for the evaluation of durability and serviceability of structures depend on exact determination of tensile strength of concrete. Thus, many researchers are interested in precise prediction of mechanical properties of SCC in order to reach a safe, serviceable and economical design [12–14]. In order to better understand the behavioral differences between SCC and NVC, abundant papers and reports have been published. Recently, due to the growing success of SCC, many conferences and RILEM Symposium have been held on assessment of different behavioral aspects of SCC in terms of mix design, chemical admixtures, rheology and workability, production and placement, flow modeling, formwork pressure, hardened properties, bond strength, structural performance, fiber-reinforced SCC, and case studies. Most researchers believe that the modification of mixture composition of concrete such as use of limestone powder, fly ash and slag and also use of higher amount of cement paste, absence of external and internal mechanical vibration, which lead to significant reduction of segregation and bleeding, reduction of air pores and lower water to powder ratio improves the quality of interfacial transition zone (ITZ), causes higher homogeneity and also remarkably improves the microstructure of SCC compared to NVC. This also makes SCC to have noticeably different properties from NVC [12–17]. However, there are substantial contradictions among the reported results. The results of previous studies indicated that the increase rate of compressive strength of SCC at early ages is higher than that of NVC. This is due to the presence of powder material and retaining capability of water in SCC [17]. On the other hand, due to presence of powder material and absence of external and internal vibration, ITZ in SCC is stronger than that of NVC and consequently compressive strength of SCC, for a specific w/c ratio, is higher than that NVC [18]. Different researchers have indicated that compressive strength of concrete depends on proportion of cement to aggregate and aggregate size as well as w/c ratio. Since, in SCC, aggregate content and size is different from NVC, it is expected that the compressive strength of SCC is affected by these variables [12–17]. Domone [16] stated that, in SCC, type and content of powder affect the compressive strength much more than w/c ratio does. Many studies on tensile strength have shown that, at a specific compressive strength, the tensile strength of SCC is slightly higher than NVC [18–22]. The reason for this slight difference is the presence of active additives in the composition of SCC. Felekoglu et al. [23] also showed that the use of limestone powder in SCC mixes with w/c ratios between 0.37 and 0.6 results in higher tensile strength for SCC compared to NVC. This is due to improved homogeneity resulting from absence of mechanical vibration. Koning et al. [18] and Hauke [19] demonstrated that tensile strength of SCC is increased by 13.5% and 9.1% respectively when fly ash is used. Fava et al. [20] showed that use of slag in SCC increases the tensile strength by 10.5%. Bosiljkov [24] also showed that SCC and NVC have the same tensile strength. It should be noted that the abovementioned results are reported for SCC with high compressive strength. In order to investigate mechanical properties of SCC in strength range of medium and low strength, Parra et al. [17], studying SCC mixes with w/c ratios of 0.45–0.65, showed that the tensile strength is 15% lower than that of NVC and thus they proposed that the existing relations in standard codes for NVC should be modified for SCC. Domone [16], collecting comprehensive data sets from extensive studies on SCC up to 2007, demonstrated that despite high scattering, tensile strength of NVC and SCC do not have noticeable difference. Leemann and Hoffmann [14] showed that SCC and NVC have the same tensile strength. Vilanova et al. [12] concluded that SCC and NVC have the same mechanical properties. They stated that ACI relations are capable of predicting tensile strength of SCC with high accuracy. Aslani and Nejadi [25] reported that, regardless of the type of aggregate and filler used in proposed models for tensile strength, SCC and NVC have roughly the same tensile strength. It is particularly worth noting that any difference between tensile strength of SCC and NVC disappears as the compressive strength exceeds 80 MPa. Many relations have been proposed for NVC to predict modulus of elasticity as a function of compressive strength. Considering obvious differences between SCC and NVC in terms of paste volume, maximum aggregate size and rheological behavior of SCC, using the proposed relations for NVC in order to predict modulus of elasticity of SCC might be controversially debatable [15]. Extensive studies have been carried out concerning modulus of elasticity of SCC, but like other mechanical properties, the result are highly contradicting, making it impossible to reach a consensus. Some researchers believe that SCC has lower elastic stiffness than NVC which is due to higher volume of paste in SCC [23,26–28]. Su et al. [29] showed that decrease of coarse aggregate to total aggregate ratio does not change modulus of elasticity of SCC. Domone [16], studying the results reported by other researchers, showed that modulus of elasticity of SCC in low strength levels is 40% lower than that of NVC while in higher strength levels this value is limited to 5%. Domone [16] believes that this behavior is attributed to lower content of coarse aggregate in SCC compared to NVC. However, Van Itterbeeck et al. [30] dose not confirm Domone' s findings. Persson [13] reported that there is negligible difference between modulus of elasticity of SCC and NVC when the strength is considered constant. Gram and Piiparinen [31] showed that SCC and NVC have the same modulus of elasticity. Dehn et al. [32] named SCC a soft concrete as it has lower stiffness than NVC. Jacobs and Hunkeler [33] found that, for a specific strength, modulus of elasticity of SCC is lower than that of NVC as smaller aggregate is used in SCC. Felekoglu et al. [23], investigating the ratios of w/c between 0.37 and 0.6, showed that modulus of elasticity of SCC is lower than NVC. Ashtiani et al. [34] reported that, at high strength levels, the modulus of elasticity of SCC is lower than NVC. Ambriose and Pera [35] as well as Bonen and Shah [36] reported that, due to lower content of aggregate in SCC, the modulus of elasticity of SCC is lower than that of NVC with the same strength. Panesar and Shindman [15] showed that, in SCC, with compressive strength higher than 50 MPa, modulus of elasticity can be predicted through AASHTO equation. Attiogbe et al. [37] concluded that SCC and NVC have the same modulus of elasticity. Holschemacher and Klug [38] also precluded that SCC has lower modulus of elasticity than NVC. Leemann and Hoffmann [14] stated that, due to higher content of paste in SCC, modulus of elasticity of SCC, with the same compressive strength as NVC is 15% lower than NVC. Parra et al. [17] showed that modulus of elasticity of SCC is only 2% lower than NVC which is due to lower stiffness of paste compared to aggregate. Chopin et al. [28] stated that the difference between modulus of elasticity of SCC and NVC is at most 5%. Vilanova et al. [12] showed that ACI318 model gives rather overestimated values for modulus of elasticity of SCC. According to the mentioned difference between mix designs of SCC and NVC and because of scattering in the results reported by researchers in the previous decade, it is important to analyze the effect of existing differences between SCC and NVC on the properties of hardened concrete. It is also essential to assess the use of all assumptions and relations that