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A comprehensive investigation into the effect of water to cement ratio and powder content on mechanical properties of self-compacting concrete

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HIGHLIGHTS

- The effect of w/c ratio and powder content on mechanical properties were studied.
- With increase of limestone powder, the compressive and tensile strengths increase.
- In lower w/c, limestone powder increases the compressive strength more noticeably.
- w/c ratio has greater effect on tensile and compressive strengths than E-modulus.

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ABSTRACT

Self compacting concrete (SCC), as an innovative construction material in concrete industry, offers a safer and more productive construction process due to favorable rheological performance which is caused by SCC's different mixture composition. This difference may have remarkable influence on the mechanical behavior of SCC as compared to normal vibrated concrete (NVC) in hardened state. Therefore, it is vital to know whether the use of all assumptions and relations that have been formulated for NVC in current design codes are also valid for SCC. Furthermore, this study presents an extensive evaluation and comparison between mechanical properties of SCC using current international codes and predictive equations proposed by other researchers. Thus, in this experimental study, key mechanical properties of SCC are investigated for sixteen SCC mixes with different w/c ratios and different powder contents. In the present study, an extensive data reported by many researchers for SCC and NVC has been used to validate the obtained results.

1. Introduction

Over the last decades, self-compacting concrete (SCC), as a new generation of high-performance concrete, has been known as a significant progress in concrete industry and consequently considered as the subject of extensive research studies [1,2]. SCC may be defined as concrete with the capacity to spread into mold and pass around the heavy reinforcements. SCC can also fill sections with more complex shapes, compacting only under its own weight without the need for internal or external mechanical vibration during the casting process. In addition use of SCC prevents segregation and bleeding [3–5]. Moreover, self compacting concrete can be pumped to a great distance and increases the speed of construction [6,7]. SCC also offers significant environmental, technical and economical benefits such as improved pore structure as a great concern in durability of special structures [8,9]. Apart from relevant research interests, applications of SCC in building industry have also increased noticeably due to the successful evolution it has brought about in the precast concrete industry in recent years [10].

Typically, in order to attain the special behavior of SCC , higher fine particle content and very powerful superplasticizers must be

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used compared to normal vibrated concrete (NVC) [11]. Many researchers reported that these modifications in the mix design may have remarkable effects on the mechanical behavior of SCC as compared to NVC in hardened state [12–14]. It has been proved that mechanical properties are directly related to mix parameters [15]. Studies on the mechanical properties of SCC have been the research interest in the recent decades [16–18]. Thus, many researchers are interested in precise estimation of mechanical properties of SCC in order to reach a safe, serviceable and economical design [16–18]. Most researchers believe that the modification of mixture composition of concrete makes SCC to have different mechanical properties from NVC [12,13,16–19]. However, there are wide contradictions among the reported results.

The results of previous studies show that the increase rate of compressive strength of SCC at early ages is higher than that of NVC. On the other hand, 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 [20]. Since, in SCC, aggregate content is different from NVC, it is expected that the compressive strength of SCC is affected by these variables [16–19]. Domone [19] 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 [20–24]. Felekoglu et al. [25] 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. Bosiljkov [26] 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 (where high contents of cement (higher than 400 kg/m^3) are used accompanied by active additions, such as fly ash or blast furnace slag).

In order to investigate mechanical properties of SCC in strength range of medium and low, Parra et al. [12], studying SCC mixes with w/c ratios of 0.45–0.65, showed that the tensile strength is 15% lower than that of NVC. Thus, they proposed that the existing relations in standard codes for NVC should be modified for SCC. Domone [19], collecting comprehensive data from extensive studies on SCC up to 2007, demonstrated that despite high scattering, tensile strength of NVC and SCC does not have noticeable difference. Leemann and Hoffmann [18] showed that SCC and NVC have the same tensile strength. Vilanova et al. [16] 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 [14] reported that disregarding 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.

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 [13]. Extensive studies have been carried out concerning modulus of elasticity of SCC, but like other mechanical properties, the results are highly contradicting, making it more difficult to reach a consensus. Some researchers believe that SCC has lower elastic stiffness than NVC [25,27–29]. Su et al. [30] showed that decrease of coarse aggregate to total aggregate ratio does not change modulus of elasticity of SCC. Domone [19], studying the results reported by other researchers, showed that modulus of elasticity of SCC in low strength levels is lower than that of NVC by 40% while in higher strength levels this value is limited to 5%. Domone [19] believes that this behavior is attributed to lower content of coarse aggregate in SCC compared to NVC. However, Van Itterbeeck et al. [31] dose not confirm Domone's findings. Persson [17] reported that there is negligible difference between modulus of elasticity of SCC and NVC when the strength is considered constant. Gram and Piiparinen [32] showed that SCC and NVC have the same modulus of elasticity. Dehn et al. [33] named SCC a soft concrete as it has lower stiffness than NVC. Jacobs and Hunkeler [34] 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. [25], 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. [35] reported that, at high strength levels, the modulus of elasticity of SCC is lower than NVC. Ambriose and Pera [36] and Bonen and Shah [37] reported that, due to lower content of aggregate in SCC, the modulus of elasticity of SCC is lower than that of NVC in the same strength. Panesar and Shindman [13] showed that in SCC, with compressive strength higher than 50 MPa, modulus of elasticity can be predicted through AASHTO equation. Attiogbe et al. [38] concluded that SCC and NVC have the same modulus of elasticity. Holschemacher and Klug [39] also precluded that SCC has lower modulus of elasticity than NVC. Leemann and Hoffmann [18] 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. [12] showed that modulus of elasticity of SCC is only 2% lower than NVC which is due to lower stiffness of paste compare to aggregate. Chopin et al. [29] stated that the difference between modulus of elasticity of SCC and NVC is at most 5%. Vilanova et al. [16] showed that ACI318 model gives rather overestimated values for modulus of elasticity of SCC.

Since SCC and NVC have different mix designs and the reported results for mechanical properties of SCC are highly scattered, it is important to analyze the effect of varying key parameters on the properties of hardened SCC. It is also essential to assess the use of all assumptions and relations that have been formulated for NVC through years of studies and carrying out experiments to see whether the relations introduced in codes and international standards are valid for SCC. In many recent studies, SCC mixes have been reported to have contained active additives like fly ash, slag, silica fume as filler and fewer studies have been carried out on the use of limestone powder which is a more economical and common filler in many countries.

In order to better understand mechanical behavior of SCC, the purpose of this study is to evaluate two parameters of w/c ratio and powder content in an extensive range including sixteen mix designs. In the present study, experiments have been carried out on 144 specimens of hardened concrete and the mechanical properties of SCC have been investigated. Consequently the ratio of test results to the predicted values, based on prediction relations for SCC proposed by different researchers as well as common prediction equations proposed by most international codes, have been investigated. It should also be noted that in the present study, an extensive body of results proposed by many researchers for SCC and NVC has been used to compare and validate the obtained results.

2. Experimental programme

2.1. Concrete mixture, materials and mixing procedure

In order to investigate the relation between mechanical properties of SCC, w/c ratio and powder content, two series of experimental programs were designed including 16 concrete mix designs. The first series consisted of 8 mixes made to investigate the effect of w/c ratio on mechanical properties of SCC when w/c ratio varies from 0.35 to 0.7. The second series was considered to evaluate the effect of limestone powder volume on mechanical properties of SCC. In this series, there were 8 mixes with two different w/c ratios of 0.47 and 0.6. In order to investigate different levels of limestone powder addition for each w/c ratio, four SCC mixes containing different amounts of limestone powder (25%, 50%, 75% and 100% i.e. ratio of limestone powder to cement by mass) are considered. In each mix design, fine