

Evaluation of Mechanical and Durability Aspects of Self-Compacting Concrete by Using Thermo-Mechanical Activation of Bentonite [†]

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Abstract: With rapid developments in the construction industry, it has become vital to develop structures and materials that are both cost-effective and environmentally sustainable in order to reduce carbon footprints. This research work aimed to inspect mechanical as well as durability aspects of self-compacting concrete (SCC) using thermo-mechanical activation and mechanical activation of bentonite as a partial replacement of cement by weight. Incorporating supplemental cementitious materials (SCMs), many researchers found that the mechanical and durability characteristics of SCC can be enhanced. Activation treatments can improve the binding capacity of bentonite and enhance its substitution level. Bentonite was replaced by weight with ordinary Portland cement (OPC) in proportions of 10%, 15%, 20%, and 25%. By introducing bentonite, the fresh characteristics of SCC were reduced but remained within the limitation given by the EFNARC. The use of thermo-mechanical activation can significantly increase both hardened and durability properties. Compressive and split tensile strength yielded the best results at 15% substitution level and were comparable at 25%. Water absorption and resistance to acid attack showed better results with an increase in bentonite content at 56 days. These findings indicate that the use of bentonite can cut CO₂ emissions while also producing long-lasting SCC at a reasonable price.

Keywords: bentonite; slump flow; self-compacting concrete; mineral admixture; acid attack resistance



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1. Introduction

Nowadays, self-compacting concrete (SCC) is certainly a usual feature of construction industries, used to minimize the challenges that come with normally used concrete. Self-compacting concrete fills the congested parts of formwork due to its own weight due to its high flowability and passing ability. Due to its ability to fill the congested parts of formwork, it excludes the use of compactors or vibrators that are normally used in ordinary concrete. By using SCC, duties of labor are limited to some extent. Pumping for longer distances is possible due to its great mobility and non-segregation property [1]. SCC has many advantages over ordinary concrete, including lower costs, improved concrete qualities, and quick construction [2].

SCC is defined mainly by two main features: Resistance to segregation and high deformability or flowability. The homogeneity and stability of SCC are due to its resistance to segregation and it providing acceptable deformability. Resistance to segregation is provided by increasing fines or by introducing a viscosity modifying admixture (VMA). These viscosity-altering chemical additives are quite costly, and they are the primary reason for SCC pricing increases [3]. Furthermore, the amount of cement needed to form a paste in self-compacting concrete is greater, resulting in an increase of heat of hydration and other environmental and economic issues linked with the usage of cement [4]. For that purpose, additions of pozzolanic as well as advanced substitution materials such as

fly ash and silica fumes are recommended for the production of SCC, which improves fresh and mechanical and durability characteristics [5]. Use of untreated bentonite as a supplementary cementations material in concrete was explored, and it was discovered that when the amount of bentonite was enhanced, the fresh properties decreased and the water absorption of concrete increased, while bentonite increased 56 days' strength. Similar trends have been observed elsewhere. Hazardous chemical penetration can be minimized by incorporating SCMs with OPC. Via the hydration process of cement, calcium hydroxide (CH) is produced as a principal by-product, which is the key focus for reinforcement corrosion. During pozzolanic activity, the pozzolanic material utilizes CH and extra gel of calcium silicate hydrate (CSH) is generated, resulting in increased strength and durability of concrete [6].

Different methods can be used to activate pozzolanic material, i.e., thermally, mechanically, and by using some chemical activation techniques. Mechanical activation entails grinding the material into powder to increase the surface area and improve the fineness of SCMs. Previous studies established that mechanical activation (grinding) increases pozzolanic responsiveness [7]. In precast concrete, self-compacting concrete (SCC) is also increasingly being used for the construction of precast sewer pipes and drainage systems that are susceptible to chemical attack. Since SCC has a different mix design than conventional concrete, its sustainability in these applications must be evaluated. In particular, SCC can be made with varying amounts of bentonite as a substitute for cement, which is done in order to improve its durability properties [8]. Heating the pozzolanic material means heating it or curing the sample made with pozzolanic material (calcination). Thermal treatment of clays results in a stable state due to its disordered structure, and a crystalline dynamic structure is formed [9].

Nowadays, calcined clays have become popular due to their ability to activate with comparatively little energy, in contrast to cement, which requires a large amount of energy to produce, and therefore they are readily available worldwide [10]. Due to the presence of moisture-liberated CH due to hydration, the cement combines with the silica (SiO_2) component of pozzolana to generate CSH gel to enhance the pozzolanic reaction [11]. Musarat et al. conducted extensive research on varying ratios of bentonite as a VMA and found that employing bentonite as VMA boosts viscosity and resistance to segregation up to the optimum amount. These findings suggest that using thermo-mechanically treated bentonite will cut CO_2 emissions [12].

The literature review indicates that there are many research works that have been carried out by utilizing bentonite as a fractional substitute of cement to make ordinary and self-compacting concrete. Hence, the main purpose of this research work was to compare the different fresh, hardened, and durability features of SCC by incorporating thermo-mechanically activated (TMA) and mechanically activated (MA) bentonite in a low impact environment. The level of substitution for both TMA and MA was at 10%, 15%, 20%, and 25% replacement by weight of cement. The tests performed were slump flow and compressive strength. Another key feature was the evaluation of some durability properties, such as water absorption and acid attack. All of these tests were performed for up to 56 days to evaluate the characteristics of SCC. Findings at 15% TMA and MA bentonite showed maximum results.

2. Materials

2.1. Cement and Bentonite

OPC was used in this work as a main binder following [13]. Bentonite is a siliceous and aluminous pozzolanic substance in powder form and the existence of moisture chemically reacts with calcium hydroxide (CH) at normal temperatures to make cementitious compounds (CSH) as shown in Figure 1. Sodium bentonite clay taken from the KPK district of Pakistan was used for the experimental work. The bentonite clay used as a pozzolana satisfied the requirements of [14]. To achieve the desired properties with a higher amount of fines, viscocrete, a widely viable high-range water reducing admixture, was used.



Figure 1. Bentonite (ground).

Fine Aggregates and Coarse Aggregates

For fine aggregate, sand from the Lawerncepur (Karachi, Pakistan) quarry was used. Margalla hill crush up to 20 mm maximum size was used to make the self-compacting concrete flowable and workable.

2.2. Bentonite Activation Techniques Used

2.2.1. Activation of Bentonite through Mechanical Process (Grinding)

The bentonite used was first oven-dried at 100 °C for 24 h. Grinding of bentonite was performed with a Los Angeles abrasion apparatus for overall 4500 revolutions for a 5 kg sample batch to continue for its uniformity. After the grinding process, sieving was carried out by sieve number 325 to check its wet passing and it was protected in a plastic bag to prevent wetness.

2.2.2. Thermal Activation of Bentonite (Heating)

A furnace was used for the thermal treatment of bentonite. Oven-dried bentonite was placed in the furnace for 3 h at 800 °C. A sample of 5 kg was placed for heating to maintain uniformity and achieve the targeted limit. After 3 h the furnace was allowed to reach room temperature, which usually takes 5 h. During this time, the clay remained in the furnace. The same process was repeated to obtain the required amount of bentonite. To protect it from moisture, the cooled bentonite was packed into plastic bags.

2.3. Mix Proportions

Ten mixes were prepared to evaluate the rheological, hardened, and durability characteristics of self-compacting concrete in this research. The compositions of the mixtures with their nomenclature are listed in Table 1. For both thermo-mechanical activation (TMA) and MA, cement was replaced with bentonite by the same percentages by mass of 5%, 10%, 15%, 20%, and 25%. Due to the incorporation of very fine bentonite, the cement's surface area increased and required a large amount of free water for wetting, and therefore different percentages of superplasticizer (SP) were used to obtain the targeted domain of workability.

Table 1. Mixture proportions for SCC.

Mix Description	W/Binder	Water Used (kg/m ³)	Cement (kg/m ³)	Bentonite (kg/m ³)	Fine AGG (kg/m ³)	Coarse AGG (kg/m ³)	SP-(%)
5B-TMA	0.40	201.30	446.11	23.48	906.22	802.14	0.8
10B-TMA			422.63				0.8
15B-TMA			399.15	70.44			0.9
20B-TMA			375.67	93.92			0.9
25B-TMA			352.19	117.4			1.1
5B-MA	0.40	201.30	446.11	23.48	906.22	802.14	0.8
10B-MA			422.63				0.8
15B-MA			399.15	70.44			0.9
20B-MA			375.67	93.92			0.9
25B-MA			352.19	117.4			1.1

3. Results and Discussion

3.1. Fresh Properties of SCC

Slump Flow

Figure 2 shows the slump flow variation for SCC with different percentages of both TMA and MA bentonite that show similarity. This figure illustrates that slump flow decreased as the addition of bentonite increased but the slump achieved for all mixes remained between 693 and 745 mm, which is categorized as SF2 defined by the EFNARC. The Figure 3 indicated the slump flow result. With the addition of SCMs, material flowability decreased, whereas it was maintained using SP addition. The addition of minerals to the concrete utilized a large portion of superplasticizer, and as a result of the quantity of superplasticizer the dispersion and deflocculating of cement grains will be precipitated partially by the application of minerals [15].

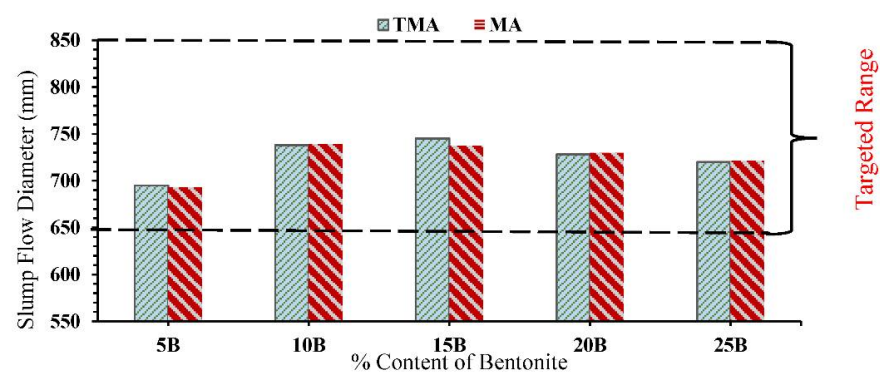


Figure 2. Slump flow for SCC with a variable amount of bentonite.



Figure 3. Slump flow test.

This observation is similar to the finding that with the increase in the amount of bentonite, the slump decreases, which requires a larger quantity of water as compared to OPC due to its large surface area of particles [16]. The slump flow diameter for 15% replacement was larger than the others. This might be due to the optimum quantity of fines that helps to deform to a larger extent; however, with the increase of bentonite quantity, the slump flow diameter decreased.

3.2. Mechanical Properties

3.2.1. Compressive Strength

The compressive strength at 7, 28, and 56 days for SCC made with TMA and MA bentonite is described in Figure 4. The compressive strength of substitution of TMA bentonite at an early age of 7 days showed similar results from 5B-TMA to 25B-TMA bentonite. Due to thermo-mechanical activation treatment of pozzolana, silica components become more active and react with the CH liberated due to hydration of cement in the presence of water. During this reaction, strength development is normally slow and the heat of liberation is lower. Furthermore, it consumes more lime rather than producing it, which has a considerable impact on durability characteristics of hcp in an acidic environment.

Strength may be enhanced as indicated by research, which found that strength development is often slow at an early age [17]. The compressive strength at 15% MA bentonite was comparable to 25% TMA bentonite. Figure 5 shows the breaking of specimens.

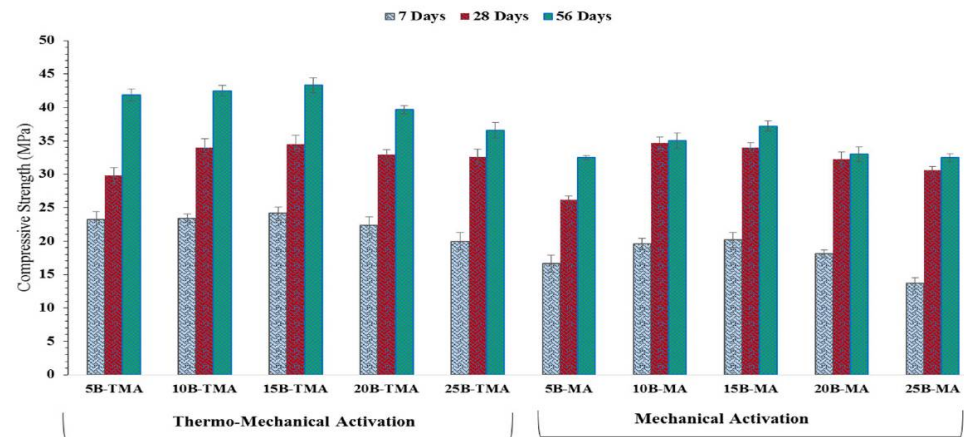


Figure 4. All mixes' compressive strength outcomes.



Figure 5. No. 1 Compressive Strength and No. 2 split tensile strength.

However, TMA bentonite substitution showed higher strength than MA bentonite. At 15% addition of TMA, the maximum result was found at 7, 28, and 56 days. The compressive strength of SCC reduced significantly as the bentonite addition increased from 20% to 25% for both MA and TMA for all ages of 7, 28, and 56 days.

3.2.2. Split Tensile Strength

The reasonable tensile strength of the sample can be estimated by the splitting tensile strength test based on its splitting failure pattern. Figure 6 shows split tensile results for all 10 mixes at 7, 28, and 56 days.

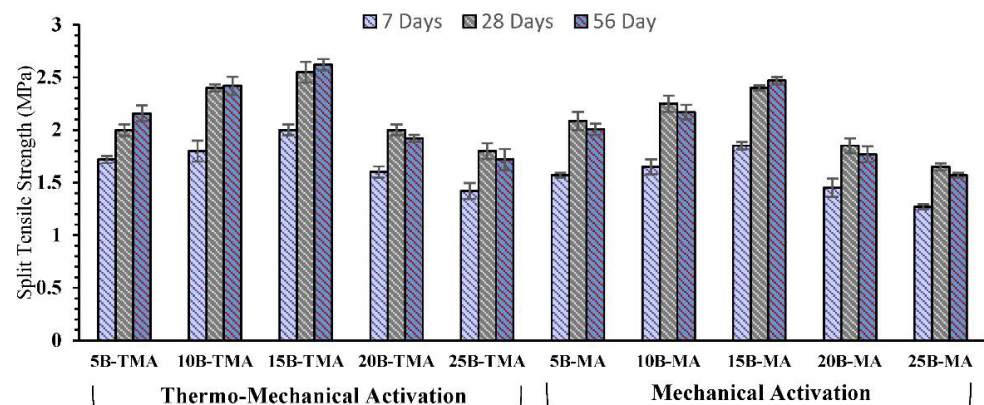


Figure 6. Split tensile strength outcomes.

A very similar trend was observed in compressive strength at 28 and 56 days. The split tensile result at 25% TMA bentonite was comparable to 15% MA bentonite substitution. At 56 days, the tensile strength of 15B-TMA was 6.5% higher than that of the 15B-MA mix, which means that TMA bentonite shows noteworthy improvement over MA, which indicates an increased reactivity of clay in pozzolanic reaction. TMA might be more sensitive to silica to react with CH [17]. The split strength of 25B-TMA at 56 days was reduced to 5.5%, whereas at 20% replacement the strength at 28 days was higher than at 56 days. This might be due to the filling effect of residual clay minerals that offers resistance to compression at a higher level but gives minimal resistance to failure for splitting tension. Thus, splitting tensile strength reduces at a higher level of substitution for both cases.

3.3. Durability Characteristics

3.3.1. Water Absorption Test

The water absorption (WA) test is a useful principle to measure the porosity of concrete in contact with water. Numerous harmful chemicals can penetrate into concrete due to voids in the concrete, react with its ingredients, and alter its material properties. The results of water absorption for all mixes of SCC at 7, 28, and 56 days are given in Figure 7.

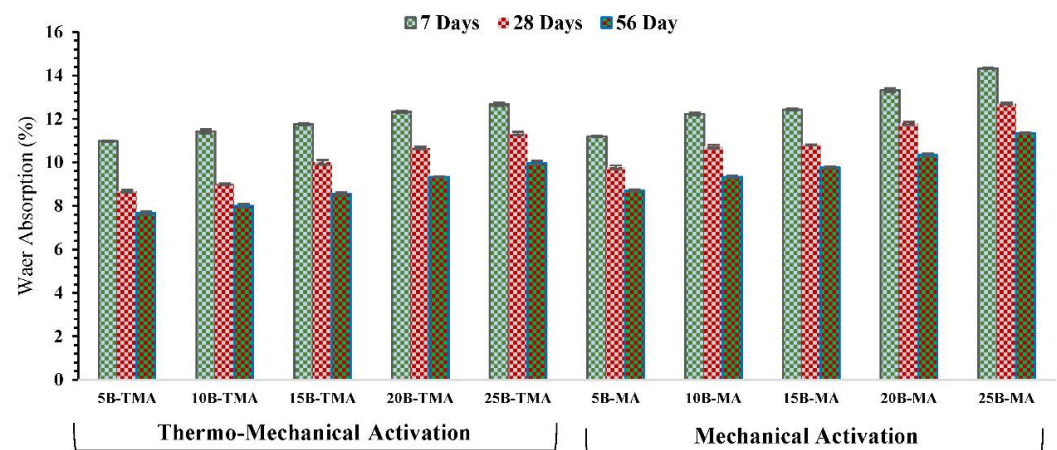


Figure 7. Water absorption results of each mix at 7, 28, and 56 days.

An increasing trend was observed with the increase of bentonite percent for all of the mixes. 15B-TMA showed 8% higher water absorption than 15B-MA, which illustrates the reactivity of the substituent increase due to the thermal process. A similar behavior was observed for 25% replacement of TMA bentonite, which was 14% lower than MA bentonite. The overall trend for all mix proportions remained an increase with the increase of substitution level.

3.3.2. Acid Attack

Concrete structures are subjected to an acidic environment susceptible to deterioration when acid-mixed water penetrates into concrete. Gypsum is produced by the reaction of sulfate ions with portlandite and reacts with aluminate hydrate to produce a sulfo-aluminate by-product. The internal pressure produced causes the concrete to swell. Due to swelling, the soft and mushy mass produced deteriorates the surface of the concrete sample.

Therefore, it is necessary to handle the amount of CH to minimize the reaction with H_2SO_4 [18]. Sulfuric acid, H_2SO_4 , was used to create an acidic environment for all mixes. The mass loss percentage for all mixes at 28 days and 56 days is shown in Figure 8. An abundant amount of CaO content is present in OPC, and on the other hand, bentonite contains a large amount of SiO_2 and Al_2O_3 [19]. Therefore, raising the amount of TMA/MA bentonite results in a reduction in CH level. It was observed that the TMA mixes offered more resistance to acidic attack than the MA bentonite mixes. TMA/MA also fills the pore spaces of concrete, preventing the penetration of SO_4^{-2} , which might be a source

of deterioration of concrete. The overall trend of the findings shows that the addition of TMA/MA bentonite significantly improved the H₂SO₄ resistance. Comparative analysis shows that the loss of mass in SCC was 3% to 4% lower than traditional concrete, which might be due to more fines and less porosity, forming a compact bound [20].

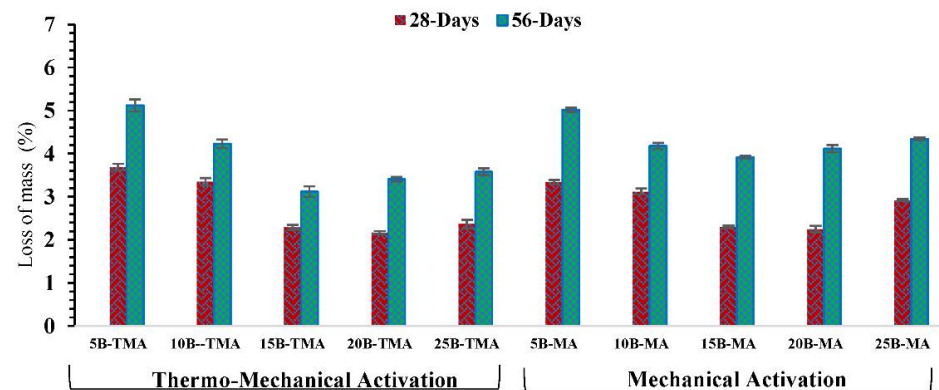


Figure 8. Loss of mass due to H₂SO₄ attack for all mixes at 28 and 56 days.

4. Conclusions

Following are the conclusions of this research work:

Fresh properties of SCC were decreased as the substitution level of bentonite content increased for both TMA and MA treatments of bentonite. However, the range for slump flow remained within the targeted domain recommended by the EFNARC for SCC production.

At 28 and 56 days, mechanical characteristics—compressive strength and split tensile strength—for both cases were at a maximum with 15% replacement of bentonite, which was comparable at 25% replacement level of (MA) mechanical activation bentonite. The overall significant positive impact was observed on durability qualities—water absorption and resistance to acid attack (H₂SO₄). Both mixes showed better results up to 15% replacement. TMA bentonite mixes showed considerably better results than MA bentonite mixes for the replacement with OPC due to their improved reactivity.

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