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The Effect of Waste Material Addition on The Physical Properties of Ternary Cement

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ABSTRACT

Cement production is a significant source of CO_2 emissions; therefore, partial replacement of ordinary Portland cement (OPC) with supplementary materials can reduce environmental impact. This study evaluates ternary blended cement incorporating locally available steel slag, calcined clay, and limestone in Iraq as partial OPC replacements. Replacement levels ranged from 30% to 60%. The effects on standard consistency, setting times, and soundness were investigated. Results showed that water demand increased with higher replacement levels, reaching 48% at 60% substitution. Slag replacement (25–30%) increased initial and final setting times by up to 29% and 45%, respectively. In contrast, calcined clay replacement (up to 35%) reduced initial and final setting times by up to 26% and 15%, respectively. Soundness values remained within acceptable limits for all mixes. The findings indicate that high-volume ternary blends can reduce clinker content while maintaining acceptable physical properties, offering environmentally and economically sustainable alternatives to conventional OPC.

1. Introduction

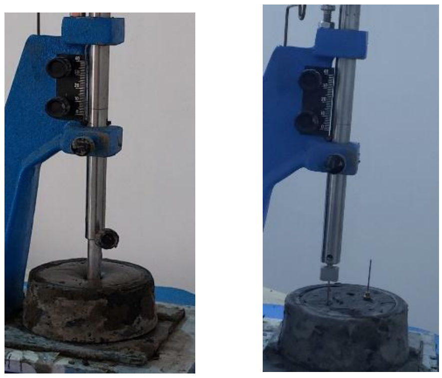
Today, supplemental cementitious materials (SCMs) are widely used in construction as a constituent of blended cement or a mineral additive to concrete. The utilization of (SCMs) and substitute gases are the common approaches approved to reduce the ecological effects of cement manufacturing used in concrete. SCMs can minimize the CO2 discharges from about 0.80 - 0.65 kg/kg of cement [1].

SCM.s are introduced as eco-friendly, profitable, and affordable substitutes. SCMs contain minerals that react chemically with calcium hydroxide at usual heat and have slight cement or pozzolanic characteristics. Generally provided as waste or a by-product from other industries, natural pozzolans, or activated minerals [2] . Common SCMs include fly ash, silica fume, slag, calcined clay, and natural pozzolan, which continues to increase annually [3] . Using SCMs for concrete provides several advantages, including greater ultimate strength; consequently, they render porous improvement and decreased permeability and im-prove concrete mechanical characteristics at later curing, including durability performance as sulfate attack resistance and alkali-silica reaction [4], prevention of surface cracking, economic benefits, and increased sustainability [5]. Since the SCMs possess various chemical and physical compositions besides different particle characteristics, they might affect the concrete's properties, including its setting properties. Awareness of setting time is vital in concrete construction. It contributes to planning the multiple phases of the construction process, including conveyance, handling, tamping, and final finishings. The setting time is crucial for concrete formwork operations. Therefore, it is considered decisive in the selection of specific SCMs. The hydration process starts rapidly when the water is mixed with the cement.

The preliminary setting time signals the beginning of the blend hardening; on the other hand, the latest setting time signals the final hardness of the concrete [6]. Phung et al.. [7] found that 10% and 20% LS were adequate alternatives for cement. Adding LS accelerated the hydration process, which lowered the setting time. Yuvrej and Manu [8] proved that limestone had a positive impact on setting time because the hydration with calcined clay and fly ash is speeded up. Soundness characterizes the paste samples that do not exhibit cracks, disintegration, or flaws resulting from extra volume variation. The most dominant reason for size change is the magnesia hydration. A correlation was exposed between the long-duration expansion of pastes moistly cured at standard temperatures and the MgO content [9] As a strict limit for cement soundness, the maximum MgO content in cement standards is 5% in China [10] and 5% in Canada [11]

Several studies have shown that incorporating these modifications has numerous advantages environmentally and economically. Studies have declared that the setting period increases as the slag content in the cement paste increases [11] . Wang et al. [3] reported f CaO as an important contributor to paste size expansion when replacing cement with steel slag.

This paper aims to inspect the combined impacts of supplementary materials in ternary cement; other researchers have not yet discussed the setting time and sound-ness effects of using such waste materials. Therefore, the study evaluates the impact of replacing OPC with ternary blends of calcined clay, limestone, and steel slag on the physical properties of cement paste, including consistency, setting times, and sound-ness.



(a) (b)

Fig. 1. Vicat apparatus test (a) normal consistency, (b) setting time.

2. Experimental Work

2.1. Material used in this paper

The cement was purchased from a local factory in the North region of Iraq. Type I Portland cement was used, which matches the ASTM C150 requirements. [10]. SCMs used in this paper include limestone powder obtained from cutting and mining stone locally available in the Mosul factories and steel slag obtained from the local industrial plant in Duhok Governorate. Calcined clay was also produced using the following method. The grains of natural clay were calcined by employing heat from a custom furnace.

Table 1. Chemical Compositions and Physical Properties of the OPC and SCMs.

Chemical Compositions	Wt (%)			
	OPC	limestone	Slag	Calcined clay
Silicon Dioxide (SiO_2)	**21.87**	**12.2**	**46.52**	**50.4**
Ferric Oxide (Fe_2O_3)	**2.41**	**1.1**	**15.8**	**7.55**
Aluminum Oxide (Al_2O_3)	**6.29**	**1.61**	**12.61**	**22.5**
Calcium Oxide (CaO)	**62.3**	**49.54**	**23.54**	**12.6**
Magnesium Oxide (MgO)	**3.42**	**2.39**	**1.48**	**3.36**
Potassium Oxide (K_2O)	**0.44**	**0.36**	**0.99**	**0.51**
Sulfate Oxide (SO_3)	**2.37**	**0.128**	**0.093**	**0.1**
Sodium Oxide (Na_2O)	**0.18**	**0.64**	**0.23**	**0.1**
Loss of ignition (LOI)	**0.94**	**31.50**	**1.21**	**3.01**
Physical properties				
Surface area m^2 /kg (Blaine Test)	**310**	**390**	**550**	**665**
Specific gravity	**3.15**	**2.7**	**2.95**	**2.44**

The temperature of the laboratory furnace was increased from room temperature to 750°C at a constant heating rate of 15°C/min and maintained at this temperature for 60 minutes [12]. The chemical composition was inspected by X-ray fluorescence, and the physical characteristics of both OPC and SCMs are illustrated in Table 1.

2.2. Preparation of test specimens and method

Paste specimens of the standard sample containing 650 g of binder and the proper amount of water was arranged to make the paste within typical consistency fulfilling the requirements of ASTM C187 [13] . These samples were blended according to ASTM C305 [14]. An autoclave prisme and setting time specimen have been prepared from the same sample. The blend proportions for consistency, setting times, and soundness with or without SCMs were from (30 -60) % substitute by weight of cement as presented in Table 2. Therefore, the water content for the standard consistency of the blended paste was determined by adding various percentages of water, which is crucial for the setting time and soundness tests. The Vicat device was utilized to predict the various ternary cement past consistencies. When the Vicats plunger penetrated the cement paste by 0.5-0.7 cm, the degree of consistency was marked as shown in Figure 1 (a). The setting time and soundness were established once the normal consistency was determined and the required amount of water was added.

The paste utilized for setting time is already used to determine standard consistency. Once the normal consistency and the required amount of water had been determined, the setting time was established, as shown in Figure 1(b). to evaluate the setting behavior, two durations of time are practiced. Two periods are called ‘‘initial and final setting time”. To determine the initial set time, a needle of 1 mm was used to penetrate the paste at 10 min breaks until the Indicator showed 0.5 + 0.05 cm from the undermost of the bottom device's frame. The final setting time was determined after replacing the thin needle (1mm) with a standard round needle The final setting time wass recorded when the replaced indicator did not make an obvious annular pattern on the paste crust, according to ASTM C187[13].

Immediately after completing the preparation of the setting time mold. The autoclave prism was prepared immediately from the sample residue of mixes. The mold was cast in equal dual layers; each one was compressed by forefingers or by compressing the paste into the angles and over the surface till a homogeneous prism was obtained. The top layer was compacted and cut off the upper surface of the molding paste by a slim-end hand tool. The exterior was flattened by a flat trowel. Subsequently, after stuffing the autoclave specimen, it was then transferred to a laboratory moisture chamber for 24 hours, and the mold was maintained in the moist closet till the test. The test was then conducted according to ASTM C 151 [15] , as shown in Figure 2.

Fig. 2. Autoclave test

Index	%				
	Cement	Calcined Clay	Limestone	Slag	w/b for normal consistency
M_0	100	0	0	0	31
M1	70	10	10	10	34
M2	60	20	10	10	37
M3	60	10	10	20	36
M4	50	25	10	15	40
M5	50	30	10	10	42
M6	50	15	10	25	39
M7	50	20	10	20	41
M8	50	10	10	30	39
M9	45	30	10	15	42
M10	40	30	10	20	44
M11	40	35	10	15	46

Table 2. mix proportion of ternary cement.

3. Results and Discussion

3.1. Consistency

The quantity of water demanded to prepare pastes for testing was determined by the Vicat apparatus according to [13] as illustrated. It was observed to increase the w/b ratio required to provide an acceptable consistency from (5-7) mm with the increasing replacement of cement content in the paste, as shown in Table (2). The results of normal consistency tests for ternary cement at different replacement percentages showed that water demand increased by up to 48% in mix M11, where 60% of the cement was replaced, due to the additional fine particles in the mix.

It has been noted in the mixtures in which the proportions of calcined raised, clay required more water than other mixtures, this can be attributed to the high fineness of the calcined clay led to expansion in the area of surface and also the shape effect of clay when the compared to the particles of cement and other SCMs [16] . However, in the mixtures in which the percentage of slag increased, the water demand had slightly decreased compared to other mixes in which the clay had increased because the particle form of sharp boundaries and the harsh exterior of the slag particles slightly affected the water demand [17] . The ternary mix combinations 40 OPC + 10% LL+20%SS + 30%CC and 40%OPC +10% LL + 15%SS + 35% CC required more water and may not be useful for structural purposes as they can lower the strength, elastic, and durability properties of mortar and concrete.

3.2. Setting time

The results of initial and final setting time tests for the various mixes of cement are illustrated in figure 3, the comparison of differences in the setting time of eleven sets of cement.

The test results showed that the initial and final setting times for M3, M6, and M8 mixes that contained 20%, 25%, and 30% of steel slag, respectively, were significantly decreased. The delay in setting time was caused by the lower reactivity of slag compared to OPC and other SCMs. Similar behavior has been recorded in recent research [18]. (Salman et al., 2017) [19] inspected the steel slag's influence on setting times. His study showed that as the steel slag content increased the initial setting time steadily increased, on the other hand, the blends of ternary cementitious materials that contain a high percentage of calcined clay with the existence of limestone and slag had decreased setting time due to high fineness of calcined clay and other SCMs compared of OPC. This can be attributed to the fact that calcined clay has higher amounts of alumino-silicate than steel slag, Therefore, it solidifies faster with the presence of limestone, which forms carbo-aluminates. and CSH, which leads to the formation of condensed microstructure, leading to a faster setting time [20] [21] .

The quickest initial and final setting times among all mixes were recorded in the M11 mix. The setting times were reduced by 25% and 15%, respectively, because the mix contained the highest amount of SCMs, which are characterized by their high-fineness particles. Fortunately, all mixes witnessed acceptable setting times and conformed to the requirements of ASTMC 150 [10] , as shown in Fig. 2. The initial time of all mixes was more than

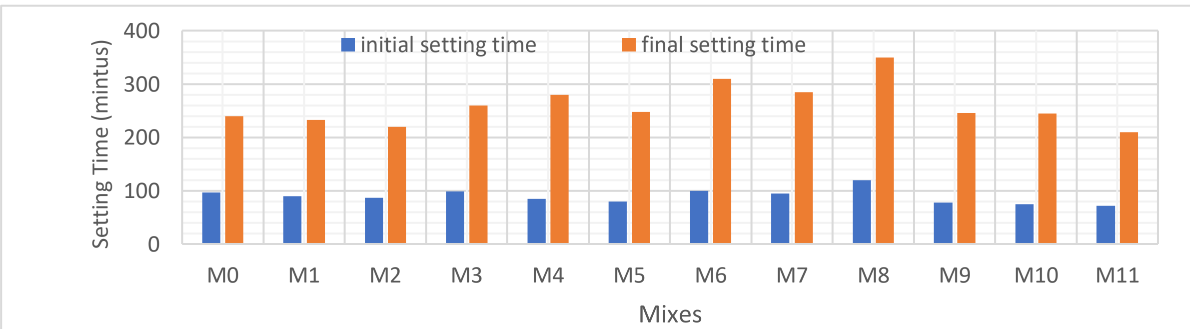


Fig. 3. Setting time of the different types of paste.

45 minutes, and the final setting time was less than 375 minutes. Long setting times (especially final) aren't usually preferred because they possibly cause high formwork costs. As a result, the final and initial setting times of mixes containing up to 60% ternary cement are considered acceptable for green concrete applications.

Table 3. Autoclave expansion of ternary cement.

Index	%				
	Cement	Calcined Clay	Limestone	Slag	Expansion
M_0	100	0	0	0	0.08
M1	70	10	10	10	0.06
M2	60	20	10	10	0.05
M3	60	10	10	20	0.03
M4	50	25	10	15	0.06
M5	50	30	10	10	0.08
M6	50	15	10	25	0.07
M7	50	20	10	20	0.05
M8	50	10	10	30	0.04
M9	45	30	10	15	0.09
M10	40	30	10	20	0.1
M11	40	35	10	15	0.2

3.3. Soundness test

An autoclave expansion test has been carried out on samples containing 0%, 30%, 40%, 50%, 55%, and 60% of ternary cement. Table 3 shows the expansion results. After the tests, no disintegration, cracks, or warping were discovered in the speci-mens. From the results, it could be concluded that all test samples conform with ASTM C150 [10] and [22] , where the autoclave expansion maximum limit of an ordinary cement or mixed mix is 0.8%. The highest expansion value was recorded in the M11 mix, 0.2%, while other mixes showed even lower autoclave expansion. Therefore, the ternary mix's expansions are very low compared to the range specified by the ASTM Standards. The expansion or unsoundness in all types of binders (cement or SCMs) happens because of the existence of free lime (CaO) or magnesia (MgO). The mentioned test is designed to estimate the (MgO) expansion. No remarkable influences are noted on the soundness of substitute cement up to 60 % by ternary cement. This could be attributed to a lower percentage of free CaO and MgO in the raw ingredients, in addition to various types of CSH and CASH formed in these blends due to the interaction of CaO, CaC03, MgO silicate, and aluminate phases during hydration; other factors can also be significant, fineness of the materials, good mineralogical and chemical for SCMs and cement [23], [24], [25].

4. Conclusion

This paper shows the physical properties of green cement paste. The results show that all the SCMs have various influences on normal consistency, setting times, and the soundness of ternary binders. Future studies should investigate the long-term du-rability and mechanical properties of ternary cement blends to further validate their suitability for sustainable construction. Generally, the paper leads to the following conclusions:

- Replacing 30% of OPC with ternary cement resulted in a minimal increase in consistency, with a 9% rise compared to plain cement paste, while replacing impact on consistency increases by up to 48 % compared to OPC when increasing the replacement of cement by ternary cement up to 60%.
- In a ternary binder consisting of limestone, calcined clay, and slag, standard consistency raises water consumption as the percentage of calcined clay increases, whereas slag somewhat lowers water demand.
- As the percentage levels of slag grow, the ternary paste's initial and final setting durations increase by 23% and 45%, respectively compared to OPC paste. This re-sults in a delay in the setting time. This phenomenon permits concrete in its fresh form to be handled for extended periods, including the advantageous delay during transit. Additionally, these mixtures help reduce the possibility of cold joints in con-crete pours.
- Increasing the replacement of calcined clay decreases the initial and final setting times by 26% and 15%, respectively, which leads to quicker framework lifting that reduces the overall costs.
- The autoclave expansion values ranged between 0.03% and 0.2% for all suggested mixes, indicating that ternary pastes with cement replacements up to 60% do not experience destructive expansion. Such mixes may well be practically implemented in concrete works.

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