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PROPERTIES OF LIGHTWEIGHT CONCRETE MADE WITH CRUSHED NATURAL POZZOLANA AS COARSE AGGREGATE

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Abstract. This paper describes a laboratory-based study examinig the use of natural pozzolana as an aggregate component in lightweight concrete (LWC). A range of conditioning variables, including cement and moisture content, storage period up to one year, was investigated.
In order to explore these effects, a series of five concrete mixes using the same Portland cement was prepared. Three mixes (LWC1, LWC2, LWC3) were designed with cement content of 400 kg/m^3 and three different W/C ratios leading to three different workability expressed with of a measured slumps of (3±1, 5±1 and 7±1) cm. Further two mixes (LWC4, LWC5) were also made with cement dosage of 300 and 350 kg/m^3 and a constant workability with a slump of 3±1cm.
The investigated properties included density, compressive strength, tensile strength and elastic modulus. The results were obtained for ages up to 365 days under different curing conditions (wet and dry).
It is concluded that LWC with pozzolana, as coarse aggregate, has sufficient strength and adequate density to be accepted as structural lightweight concrete.

Keywords: lightweight concrete, lightweight aggregate, pozzolana, mechanical properties, compressive strength, tensile strength, natural materials.

1. Introduction

In concrete construction, self-weight represents a very large proportion of the total load on the structure; and there are clearly considerable advantages in reducing the density of concrete. One of the ways to reduce it is to apply lightweight aggregate to get lightweight aggregate concrete (LWAC).

The benefit of lightweight aggregate as structural material has been recognised as far back as Roman days. In the second century AD, the Romans built the 44 m diameter dome of the Pantheon in Rome using natural pumice aggregate. The modern lightweight industry dates back to 1917 when S. T. Hayde developed a process for expanded shale and clay to form hard lightweight material called haydite, suitable for making concrete of substantial strength and low density (ACI 213R-1979).

Since that date lightweight concrete has been used for many civil engineering applications as a very convenient alternative to a conventional concrete.

Many authors in their investigations [1–6] reported that LWC has obvious advantages of higher strength/weight ratio, better tensile strength, lower coefficient of thermal expansion, and superior heat and sound insulation.

Furthermore, with a lighter concrete, the formwork can withstand a lower pressure than would be the case with ordinary concrete; also the total weight of materials to be handled is reduced.

More studies reported that the reduction in dead weight of a construction by the use of lightweight aggregate could result in a decrease in cross-section of columns, beams, plates, foundations etc.

And finally, the reduced weight may make LWC preferable for structures in seismic zones, because of the reduced dynamic actions.

With the rapid development of concrete technology in recent years, a high-performance concrete has been produced more easily. Since 1980, several investigations on high-performance LWC has been reported, studies prepared by Zhang and Gjorv [1, 2] on lightweight concrete containing expanded clay type aggregates, reported a 28-day compressive strength of 102,4 MPa.

Alduaidj, *et al* [3] studied lightweight concrete in coastal areas by using different unit weight aggregates including lightweight crushed bricks, lightweight expanded clay, and normal-weight gravel without the use of natural fine aggregates (no-fines concrete). They obtained a lightweight concrete with 22 MPa cylinder compressive strength and 1520 kg/m^3 dry unit weight in 28 days.

An important point to be mentioned is that all research carried out on the influence of lightweight aggregate characteristic of the properties of concrete, showed, however, that each type of lightweight aggregate has its own characteristics and is, in general, different from those of other aggregates. This suggests that the properties of a lightweight concrete cannot be generalised to all types. Therefore it is desirable to investigate the properties and behaviour of each type of available lightweight concrete more comprehensively.

Considering the availability of pozzolana in Algeria and its usability as a natural aggregate for concrete, a research programme has been developed in order to verify the mechanical properties of the pozzolana concrete. The main results at the actual stage of this research are presented in the paper.

2. Materials

The concrete mixtures were prepared at the laboratory of the Civil Engineering Department, ENSET Oran (Algeria), using cement and aggregates.

2.1. Cement

The cement used was a blended Portland cement type obtained from an Algerian factory situated in the West of Algeria (Zahana factory), having a 28-day compressive strength of 550 MPa and a specific gravity of 3,15 g/cm^3. The initial and final setting times of the cement were 2 h 50 min, and 3 h 50 min, respectively. Its Blaine specific area was 3140 cm^2/g. Its chemical properties are in Table 1.

2.2. Aggregates

2.2.1. Coarse aggregates

Crushed pozzolana was used as the aggregate in the production of LWC. Pozzolana was obtained from natural deposits in North-west of Algeria (Bouhamidi Source situated at about 100 km from Oran). Its chemical properties in Table 1.

Crushed pozzolana aggregates were separated according to their size into 3 groups of 0/2, 2/8, and 8/16 mm. The first one (0/2) is lightweight fine aggregate (LWFA), while 2/8 and 8/16 are coarse lightweight aggregate (LWCA1 and LWCA2) respectively.

A knowledge of the characteristics of the lightweight aggregate (LWA) is of prime importance to the designer and user of LWAC. Standard tests were performed on these locally available aggregates to determine their physical properties. The tests included visual examination of shape and texture and other tests for specific gravity, bulk density, water absorption and particle size grading of aggregates. The results are in Table2.

The aggregate particles were somewhat roughly cuboids and not of flaky character, free from any coating of dust and clay. The surface texture was relatively rough macroscopically. A high roughness of the aggregate may increase the bond strength between cement paste and aggregate. More than a half of the 24 h water absorption occurred within the first 30 min.

2.2.2. Fine aggregate

The fine aggregate was local, natural and non-reactive sand. The physical properties of the crushed sand: relative specific density 2,65, relative particle density (including pores) 2,55, water absorption 1,5 %, bulk density 1 505 kg/m^3 and a maximum grain size 2 mm.

3. Preparation and casting test specimens

To achieve a desired mix for this investigation, a large number of trial mixes were made to obtain a desired slump,

Table 1. Chemical compositions of cement and pozzolana

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_3	SO_3	CaO free	Loss by ignition
Cement	20,91	5,52	3,56	63,50	0,64	0,13	1,23			2,79	2,35	1,19
Pozzolana	46,4	17,5	9,69	9,90	2,42	3,3	1,51	2,1	0,8	0,83		5,34

Table 2. Physical properties of lightweight coarse aggregates

Types of aggregates	Dmax mm	Specific density g/cm^3	Particle density g/cm^3	Bulk density g/cm^3	Water absorption (% by weight)				
					5 min	30 min	60 min	24 h	max
LWCA1	8	2640	1,6	0,88	2,4	5,9	7,2	11,8	27
LWCA2	16	2,64	1,3	0,75	1,8	5,5	6,3	9,8	22,1

fresh concrete density about 1 800 kg/m^3 and desired compressive strength. The method adopted for the design was experimental.

The fine particles of the pozzolana aggregates (those having a diameter smaller than 2 mm) were replaced by normal weight sand. Thus a stiffer and stronger cement paste was obtained than the one produced by using lightweight sand. Further, a better workability and contained shrinkage were obtained for the concrete, but this improvement is achieved at the cost of the density increase.

In all the concrete mixes, the coarse aggregate was composed of the nominal LWCA2 and the LWCA1 fraction combined in the proportions of 2:1 by weight.

Pre-soaked aggregates were used throughout the research. The coarse aggregates were weighed in a room dry condition, then they were immersed in water for 24 h, the excess water was decanted and the water retained by the aggregate determined by the weight difference.

A series of five concrete mixes using the same cement was prepared. Three mixes (LWC1, LWC2 and LWC3) were designed with cement content of 400 kg/m^3 and three different W/C ratios leading to three different workability expressed with a measured slumps of (3±1, 5±1 and 7±1) cm. Further two mixes (LWC4 and LWC5) were also made with cement dosage of 300 and 350 kg/m^3 and a T (Table 3).

Table 3. Details of concrete mixes

Mix N	LWC	LWC2	LWC3	LWC4	LWC5
Cement, kg/m^3	414	410	405	366	312
Coarse aggregate, kg/m^3	585	578	574	575	564
Sand, kg/m^3	613	604	600	654	704
Water, l/m^3	168	180	190	173	177
Abs. water, l/m^3	54	53	53	53	52

4. Test results and discussion

4.1. Density

The slump and density of each concrete batch were determined immediately after mixing. The average value of the fresh concrete density of all mixes was between 1 810 and 1 834 kg/m^3 and is included in Table 4, along with the density data for 1, 3, 7, 28, 90 and 365 days of age for all mixes.

The density of the wet cured specimens increases with age (due to the absorption of the aggregate). The increase is about 30 l/m^3. On the other hand, there is a decrease for the dry cured specimens, the loss is about 75 l/m^3.

As expected, the density of hardened concrete increases with cement content and reduces with an increase of water.

The comparison of the unit weight of all mixes with a normal weight concrete (NWC) shows that LWAC (lightweight aggregate concrete) has a reduced average dead weight of 20 %, if one takes the density of NWC as 2 300 kg/m^3. This also means that the earthquake forces will be reduced by about 20 %, if a structure was made with LWAC.

4.2. Compressive strength

Effect of age

Compressive strength development was examined up to an age of one year. Table 5 illustrates the gain in compressive strength for all mixes. It can be seen that for any type of concrete the compressive strength increases rapidly during the first few days up to 28 days of curing, after which the gain in strength increases at a relatively slow rate for two curings of the regime.

After 3 days approx 70 % of the 28-day compressive strength was developed and 85 % will be reached in 7 days. Such fast strengthening can be explained, possibly, by the result of a high internal curing temperature developed during hydration, or/and by improving the interfacial bond of the LWA to the cement paste. Another reason of this improvement can be the reaction between the silica in the aggregate and the free lime in cement which cause a more rapid strengthening.

The 90-day strength was an improvement of about 5 % over the 28-day strength, and the 365-day strength was of about 10 %. This value is typically less than that for NWC [9]. This may be explained that the compressive strength had probably reached an upper level for the aggregate, and the strength did not benefit very much from a further increase of the mortar strength.

Effect of cement content

It can be seen in Table 5 that increasing the amount of cement content increases slightly the mix density.The reason for this is that the specific gravity of the cement is higher than that of other ingredients.

For a given workability (keeping the slump constant at 3 ± 1 cm), the strength increases with cement content. It can be seen that when cement dosage increased from 300 to 350 and 400 kg/m^3, compressive strength increased by 24 % and 21 % respectively. An increase in cement content resulted in a lower aggregate–cement ratio and a higher availability of cement paste to bond the aggregate particles. However, the rate of increase was less pronounced for 350 to 400 kg/m^3 than that obtained for 300 to 350 kg/m^3.

A visual examination of the interfacial zone indicates that the aggregate surface is not as smooth as normal aggregate. At the surface of the LWA, cement paste is trapped in the pores of the LWA to some depth. The presence of surface pores provides the interlocking site for cement paste to form a better interfacial bond between aggregate and mortar at the IZ.

Effect of water cement ratio

With the same cement content mixes with a low water/cement ratio gain strength, expressed as a percentage of 28-day compressive strength more rapidly than mixes with higher ratios. This is because in the former case the cement grains are closer to one another and a continuous system of gel is established more rapidly.

It can be concluded that the compressive strength development of LWC, as in NWC, is related to the W/C ratio and tests results have shown that strength of LWC is less sensitive to changes in W/C ratio than NWC [9].

Influence of curing types

The effect of curing regimes on compressive strength can be seen in Table 5. The two curing conditions indicate that both wet and air-dried curing provide the same effect on strength development of LWAC. Any significant difference between wet and dry cured compressive strength has been detected, the improvement was modestly higher under wet conditions, and this may be explained by a high water absorption of lightweight aggregates. Presumably it will allow dry cured specimens to have a sufficient reservoir of absorbed water for the hydration to go along at the same rate as wet cured concrete.

Material efficiency

Table 6 shows the relationship between the 28-day material efficiency (compressive-strength/density ratio) and cement proportion for lightweight concrete (LWC) and normal weight concrete (NWC) [9]. The results clearly demonstrate that this LWAC had a high material efficiency.

Table 4. Effects of age and curing conditions on density

	DENSITY, kg/m^3													
Mixture	Slump cm	Fresh	1 day	3 days		7 days		28 days		90 days		365 days	
				Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
LWC1	2	1834	1832	1844	1806	1847	1791	1850	1781	1855	1775	1862	1764
LWC2	5	1825	1821	1831	1789	1836	1771	1841	1760	1853	1754	1853	1748
LWC3	7	1821	1820	1834	1787	1837	1771	1840	1759	1849	1752	1848	1749
LWC4	3	1820	1818	1827	1783	1832	1766	1836	1754	1840	1750	1842	1741
LWC5	2,5	1810	1805	1812	1778	1817	1763	1823	1745	1826	1741	1832	1736

Table 5. Effects of age and curing conditions on mechanicals properties

Mix	Age Days	Compressive strength, MPa		Splitting tensile strength, MPa		Flexural tensile strength, MPa	
		Wet	Dry	Wet	Dry	Wet	Dry
LWC1	3	25,6 (0,73)	24,1 (0,76)	2,02 (0,69)	1,54 (0,70)	3,54 (0,80)	2,59 (0,72)
	7	32,4 (0,92)	30,3 (0,96)	2,51 (0,86)	1,99 (0,91)	4,41 (0,88)	3,32 (0,93)
	28	35,2	31,7	2,92	2,2	5,02	3,59
	90	37,4 (1,06)	34, (1,07)	3,06 (1,05)	2,45 (1,11)	5,46 (1,09)	3,63 (1,01)
	365	39,1 (1,11)	35,8 (1,13)	3,08 (1,06)	2,54 (1,16)	5,4 (1,08)	4,19 (1,17)
LWC2	3	22 (0,69)	20,4 (0,69)	1,78 (0,68)	1,34 (0,65)	3,25 (0,77)	2,28 (0,68)
	7	28,2 (0,88)	26,4 (0,90)	2,22 (0,84)	1,74 (0,85)	3,96 (0,87)	2,94 (0,88)
	28	32,1	29,5	2,64	2,06	4,55	3,35
	90	34, (1,06)	30,9 (1,05)	2,83 (1,07)	2,24 (1,09)	4,75 (1,04)	3,55 (1,06)
	365	35,5 (1,11)	32,5 (1,10)	2,91 (1,10)	2,29 (1,11)	4,94 (1,09)	3,65 (1,09)
LWC3	3	20, (0,67)	19,2 (0,69)	1,66 (0,67)	1,28 (0,66)	3,1 (0,70)	2,22 (0,68)
	7	25, (0,84)	23,6 (0,85)	2,06 (0,83)	1,60 (0,82)	3,75 (0,85)	2,76 (0,84)
	28	29,7	27,8	2,49	1,95	4,41	3,27
	90	31,2 (1,05)	29,7 (1,07)	2,64 (1,06)	1,97 (1,01)	4,58 (1,04)	3,25) (0,99)
	365	32,6 (1,10)	31,1 (1,12)	2,73 (1,10)	2,16 (1,11)	4,72 (1,07)	3,52 (1,08)
LWC4	3	19,7 (0,68)	18,8 (0,71)	1,61 (0,66)	1,15 (0,61)	2,9 (0,69)	1,97 (0,63)
	7	24,8 (0,86)	23,8 (0,90)	2,01 (0,82)	1,48 (0,78)	3,65 (0,86)	2,52 (0,80)
	28	29	26,5	2,45	1,89	4,2	3,14
	90	31 (1,07)	28,9 (1,09)	2,52 (1,03)	1,9 (1,01)	4,32 (1,03)	3,08 (,98)
	365	32,1 (1,11)	30,2 (1,14)	2,66 (1,09)	1,98 (1,05)	4,63 (1,10)	3,21 (1,02)
LWC5	3	16, (0,68)	15, (0,69)	1,27 (0,65)	---	2,36 (0,66)	1,65 (0,63)
	7	19,7 (0,84)	18,2 (0,84)	1,53 (0,79)	1,18 (0,76)	2,93 (0,84)	2,15 (0,82)
	28	23,4	21,8	1,95	1,56	3,55	2,62
	90	24,9 (1,06)	23,6 (1,08)	2,07 (1,06)	1,61 (1,03)	3,66 (1,05)	2,69 (1,03)
	365	25,9 (1,11)	24,2 (1,11)	2,16 (1,11)	1,69 (1,09)	3,82 (1,09)	2,85 (1,09)

The data in parentheses are ratios of 28-day mechanical strength (compressive, splitting tensile and flexural tensile).

4.3. Tensile strength (splitting tensile strength and flexural strength)

Results of splitting tensile strength along with flexural strength for different types of concrete employing various mixes under different curing conditions are presented in Table 5.

It can be observed that, similar to the compressive strength, the splitting tensile strength and the flexural tensile strength improved with cement content.

For a given cement content (LWC1, LWC2 and LWC3) the split tensile and flexural strengths increase with reduction in the W/C ratio.

The splitting tensile strength of the continuously water-cured concrete is between 1,95 and 2,92 MPa at 28 days. These values are only 8,5 % of the corresponding compressive strengths. While for the dry-cured specimens it is between 1,56 and 2,2 MPa, and are only 7 % of the corresponding compressive strengths.

On the other hand, the flexural tensile strength is between 3,55 and 5,02 MPa for the cured concrete and between 2,62 to 3,59 MPa for the dry cured ones at 28 days. These values are 14,5 % and 11,5 % of the corresponding compressive strengths for the wet and the dry cured mixes, respectively.

The flexural strength yields to a higher value than the splitting tensile strength (this may be related to the assumption of the shape of the stress block). In that case we can say that the flexural tensile strength is related to the splitting tensile strength by the following equation:

$$\sigma_{tensile} = 0{,}6\sigma_{flexural}.$$

These results show that splitting tensile strength and flexural tensile strength of LWC were more sensitive to drying curing conditions than the compressive strength. The dry curing of LWAC decreases the tensile strength by 25 %. The phenomenon may be explained by differential moisture distribution throughout the test specimen. This differential moisture content causes internal stress conditions resulting in a lower tensile splitting strength. However, this is less pronounced than the case of NWC [9] stored in dry condition; here as well this is due to the water absorbed by the lightweight aggregate.

4.4. Modulus of elasticity

Table 7 shows the results of modulus of elasticity for LWAC. This modulus varied from 15,0 to 21 GPa in 28 days, which was very much lower than that of NWC.

It can be observed that, similar to the compressive strength, the rate of gain for the modulus of elasticity is rapid, up to 28 days of curing; then it slows down with an additional curing time.

Table 7 shows also the variation in elasticity modulus with a cement dosage. When cement dosage increased from 300 to 350, 400 kg/m^3, the modulus of elasticity increased by 21 %, 64 % respectively.

The E values of the concrete at all ages seem to be less sensitive to the differing curing regimes adopted in this investigation. Perhaps the presence of inner reservoir of water in porous aggregate particles and the resultant of on going hydration, irrespective of the exposure conditions, has not caused any degrading effect of the E value.

Table 6. Material efficiency

Mix	Cement, kg/m^3	Unit weight, kg/m^3	Compresive strength, MPa	ME %
LWC1	400	1850	35,2	1,89
NWC1	400	2355	39,5	1,68
LWC4	350	1836	29,0	1,58
NWC4	350	2340	30,5	1,30
LWC5	300	1823	23,4	1,28
NWC5	300	2350	25,5	1,.09

Table 7. Effects of age and curing conditions on the measured and estimated modulus of elasticity

Mix	Cement	W/C		Measured modulus of elasticity, MPa			Estimated modulus of elasticity, MPa		
				7	28	365	7	28	365
LWC1	414	0,406	Wet	19446	21910	23290	19428	20300	21604
			Dry	18100	19261	20032	17940	18197	19061
LWC2	410	0,439	Wet	18940	20590	22237	17964	19244	20436
			Dry	16472	18105	18648	16466	17244	17915
LWC3	405	0,469	Wet	17478	19420	20003	16928	18496	19504
			Dry	15520	17230	18091	15569	16726	17540
LWC4	366	0,473	Wet	16995	19310	20469	16791	18217	19260
			Dry	15051	16911	17757	15568	16261	17166
LWC5	312	0,567	Wet	14961	17101	18191	14782	16190	17160
			Dry	13624	15510	15540	13579	14635	15300

The relationship between static modulus and compressive strength was investigated using the available formulae given by other investigators to correlate these two parameters. Among those, Neville [10] reported an expression as given below which relates the static modulus of elasticity to the density and compressive strength.

The calculated value of E, using the ACI 318-89 (revised in 1992) [11] expression of

$$Ec = 0{,}043\ \rho^{1,5} \sqrt{fc}\ \ \text{MPa},$$

where fc is the cylinder strength.

It has been suggested that the above expression can be used for concretes with density between 1 440 and 2 480 Kg/m^3 which covers a wide range of available LWC. The actual static modulus obtained were compared with calculated values obtained from ACI equation and are in Table 7. It is clearly shown that the results confirm the applicability of the ACI equation for estimating the static modulus of LWC with pozzolana as coarse aggregate.

5. Conclusions

Based on the results of this investigation, the following conclusions are obtained:

- The mixes satisfy the criteria of structural lightweight concrete as ASTM C330 [12], which require minimum 28 days cylinder compressive strength of 17 MPa and maximum dry density of 1850 kg/m^3.
- The compressive strength of LWC seems to be less sensitive to lack of curing than NWC. This is attributed to the "inner water" stored in the porous aggregate of the LWC. However, further effect of long-term strength development for more than one year must be investigated in order to be more conclusive.
- As expected, the best strength development of all the specimens took place under water curing.
- The crushing strength is related to the cement content and the total water/ cement ratio.
- At the age of 28 days, the indirect tensile strength and flexural strength of LWC were found to be about 1/8 and 1/12 of their compressive strength, for the wet cured mixes.
- Due to the high absorption of these LWA, the absorbed water during mixing helps hydrate the cement particles at the interfacial zone, which also increases the bond between aggregate and mortar phase.
- The modulus of elasticity can be estimated by the ACI formula [11].

Since pozzolana is used only by Algerian cement manufacturers in producing blended Portland-pozzolan cements, it can be concluded that crushed pozzolana can be applied as coarse aggregate for making concrete of moderate strength with an appreciable reduction in weight and cost of construction.

Recommendation for future work:

For better understanding the behaviour of lightweight concrete with pozzolana as aggregate, it would be useful to test dry, wet and saturated coarse aggregates and to see their effect on the concrete properties. A range of significant properties such as dimensional stability, durability and permeability should be considered as well.

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LENGVOJO BETONO, GAMINTO IŠ GAMTINIO PUCOLANO IR NAUDOJAMO KAIP STAMBUSIS UŽPILDAS, SAVYBĖS

M. Mouli, H. Khelafi

Santrauka

Aprašomi laboratoriniai tyrimai, kurie buvo atliekami siekiant nustatyti gamtinio pucolano naudojimo užpildu lengvajam betonui (LB) gaminti. Buvo tiriama daug kintamųjų, kaip antai cemento kiekis, drėgnumas, laikymo trukmė iki vienerių metų. Minėtų kintamųjų poveikiui nustatyti buvo pagaminti penki betono mišiniai, naudojant tą patį portlandcementį. Trys mišiniai LB1, LB2 ir LB3 buvo pagaminti iš cemento, kurio tūrio masė lygi 400 kg/m^3, tačiau su trimis skirtingais V/C santykiais, lemiančiais betono technologiškumą, o kartu turinčiais skirtingą slankį, atitinkamai: 3 ± 1 cm, 5 ± 1 cm ir 7 ± 1 cm. Du likę mišiniai LB4 ir LB5 buvo pagaminti iš 300 kg/m^3 ir 350 kg/m^3 tūrio masės cemento, kurių technologiškumas ir slankumas toks pats – 3 ± 1 cm. Buvo tiriamos šios medžiagų savybės: tankis, gniuždomasis ir tempiamasis stipris, elastingumo modulis. Tyrimo rezultatai buvo gauti laikant medžiagas skirtingomis sąlygomis (sausoje ir drėgnoje aplinkoje) iki 365 dienų. Daroma išvada, jog lengvasis betonas, pagamintas naudojant pucolaną kaip stambųjį užpildą, turi pakankamą stiprumą ir tankį, kad būtų naudojamas konstrukcijoms betonuoti.

Reikšminiai žodžiai: lengvasis betonas, lengvasis užpildas, pucolanas, mechaninės savybės, gniuždomasis, tempiamasis stipris, gamtinės medžiagos.

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